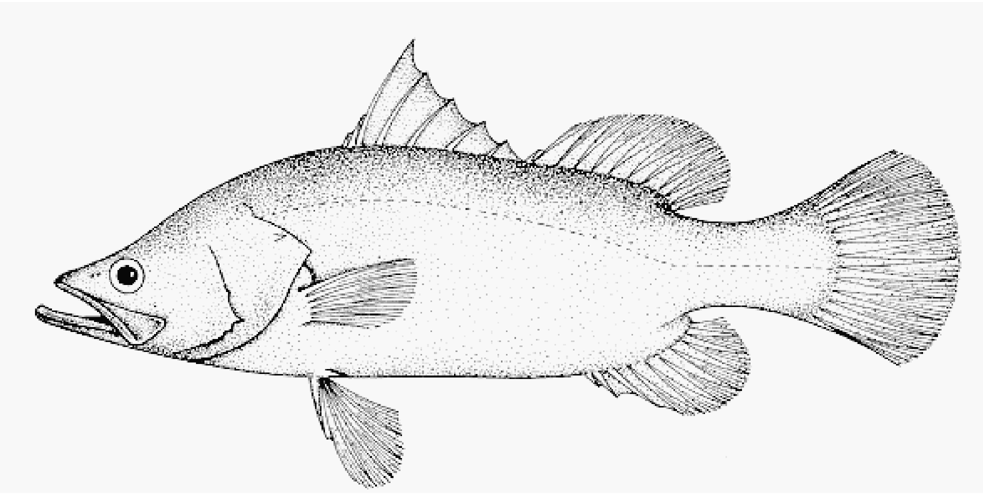
AN EXAMINATION OF THE IMPACTS OF CLIMATE VARIABILITY AND CLIMATE CHANGE ON THE WILD BARRAMUNDI (*Lates calcarifer*): A TROPICAL ESTUARINE FISHERY OF NORTH-EASTERN QUEENSLAND, AUSTRALIA.



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for the degree of Doctor of Philosophy
in the School of Earth and Environmental Sciences
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ABSTRACT

Scope

As is the case overseas, the wild fisheries of Australia are under increasing threat from the pressures of over-fishing, habitat destruction and water quality degradation. In addition, inshore fisheries that are dependant on freshwater flows to provide nutrient pulses and nursery habitats are also affected by changes in natural flow regimes as a result of water impoundment and extraction (Robins, Halliday *et al.* 2005). The barramundi (*Lates calcarifer*) is an important commercial fish species in Australia worth $8.8 million in 2004/05 (ABARE 2006), and supports valuable tourism and recreational fishing industries. Commercial catch displays a high degree of inter-annual variation; a characteristic that many fishers believe is the result of climate variability. However, apart from rainfall and freshwater flow, previous studies of the barramundi have not examined the impacts from climate in any detail, and existing management strategies do not consider natural climate variability or climate change. This study examined the effects from long-term (biannual to decadal) and short-term (inter-annual) climate variability, extreme and threshold climate events, and anthropogenic climate change on the commercial catch of wild barramundi in north-east Queensland. The possibility of incorporating climate parameters into the management of the fishery was also examined.

Methods

A life cycle model of the barramundi was developed to link climate parameters with the complex developmental stages of the species from spawning in the estuary through maturation in freshwater rivers. Fisheries and climate data were extracted from a variety of sources and compiled for analysis. A gamma distributed logarithm link function model was constructed to calculate total freshwater flow for those years when records were incomplete. Correlation analysis identified significant relationships between climate parameters and catch, and forward stepwise ridge regression was used to develop a model of barramundi catch using climate parameters as predictors. The impact of threshold events was determined by non-linear analysis and the effects of extreme events on barramundi habitat were qualified against MODIS satellite imagery.

A selection of climate change scenarios from a range of global climate models (GCMs) were run through the predictive model developed to determine the likely impacts of future anthropogenic climate change on the fishery.

Results

In the near-pristine Princess Charlotte Bay area, warm sea surface temperatures, high rainfall, increased freshwater flow and low evaporation (all measures of an extensive and productive nursery habitat) were significantly correlated with barramundi catch two years later as recorded by the CFISH logbook system. These results suggest that early barramundi survival is enhanced in these conditions. Catchability was significantly increased after high freshwater flow and rainfall events in the year of catch, a result that reinforced previous observations that mature fish in freshwater habitats are flushed into the commercial estuarine fishery. October – December rainfall and April – June flow showed non-linear asymptotic relationships, and annual evaporation a quadratic relationship, with commercial catch two years later. Curves peaked at approximately 325 mm, 245 000 Ml and 2 000 mm respectively, a result that demonstrated that once these hydro-meteorological threshold events occurred, the response from the fishery was reversed and subsequent commercial barramundi catch reduced. A comparative analysis of data from the Fitzroy River area, a catchment and near shore area that has been highly modified by human intervention, showed only increased freshwater flow prior to the wet season enhanced subsequent barramundi catch. This result indicated that the anthropogenic changes to habitat either affected or masked the relationship between other climate variables and barramundi catch in the area.

Total long-term barramundi landings as recorded by the Queensland Fish Board for six regions along the north-east coast of Queensland showed a near decadal cycle. Correlation analyses returned significant relationships between catch and the January – March average *L*-index (a measure of the latitude of the subtropical ridge) two, three and four years prior to catch, and the Quasi-biennial Oscillation (QBO) three and four years prior to catch. These results suggest that each of these cycles affects climate in the north-east Queensland region and subsequent survival of barramundi in the early life cycle stages, and provides an opportunity to estimate catch a number of years in advance.

A forward stepwise ridge regression model was built to predict commercial barramundi catch in Princess Charlotte Bay. The model contained July – September rainfall and annual evaporation two years prior to catch and explained 62% of the variance in catch and had a cross validated predictive R^2 of 59%. A second model also contained April – June flow in the year of catch (a measure of catchability). This second model explained 69% of the variance in catch and had a cross validated R^2 of 61%, however, the improvement was not statistically significant.

Using the nine global climate models in the OZCLIM program set for three initiating TAR SRES markers (A1B, A2 and B1), a suite of twelve climate change scenarios was generated for the years 2030 and 2070 for Princess Charlotte Bay. These scenarios were then run through the predictive barramundi model developed. Results indicated that due to a likely increase in annual evaporation, barramundi catch in the area will decrease for all future climate scenarios including those that show an increase in July – September rainfall. An analysis to calculate future sea surface temperatures using REEFCLIM indicated that, depending on the availability of suitable habitats, it is possible that the range of the species will extend further south by up to 800 km by the year 2070 as temperatures increase.

Conclusions

Results from this study indicate that a significant proportion of the variability seen in commercial barramundi catch in north-east Queensland is driven by variability in climate. Climate signals are significant at both short and long-term time frames and for some variables the impact is non-linear beyond a defined threshold. Anthropogenic changes to the fishery habitat alter or mask the relationship between climate and barramundi catch, and possibly affect the reproductive success of the species. The likely impact of future anthropogenic climate change will be a reduction in barramundi catch in areas where an increase in evaporation results in a subsequent decrease in shallow wetland habitats essential for early life cycle survival. This thesis provides supporting evidence for policy makers to improve significantly both the prediction of future barramundi catch and the sustainable management of the species by considering the impacts of climate variability and climate change on the species, and by incorporating climate variables into catch models.

ACRONYMS

ACW	Antarctic Circumpolar Wave
BOM	Bureau of Meteorology (Australia)
CPUE	Catch per Unit Effort
CSIRO	Commonwealth Scientific Industrial Research Organisation
ENSO	El Niño Southern Oscillation
IPO	Interdecadal Pacific Oscillation
ITCZ	Intertropical Convergence Zone
JCU	James Cook University
LSTR	Latitude of the Sub-tropical ridge
MJO	Madden Julian Oscillation
NSW	New South Wales
NT	Northern Territory
PDO	Pacific Decadal Oscillation
QBO	Quasibiennial Oscillation
QDNRW	Queensland Department of Natural Resources and Water
QDPI&F	Queensland Department of Primary Industries & Fisheries
QFMA	Queensland Fisheries Management Authority
QLD	Queensland
SA	South Australia
SAM	Southern Annular Mode
SO	Southern Oscillation
SOI	Southern Oscillation Index
SPCZ	South Pacific Convergence Zone
SST	Sea Surface Temperature
SSTs	Sea Surface Temperatures
TAS	Tasmania
TRAP	Tropical Resource Assessment Program
VIC	Victoria
WA	Western Australia
ZWW	Zonal Westerly Winds

GLOSSARY

Carnivore	Animals that feed on other animals
Catadromous	Fish that migrate from fresh to salt water for spawning
Convection	Transfer of heat through fluids, such as air or water, brought about by the movement of the fluid in question
Diadromy	Fish that normally, as a routine phase of their life cycle, and for the vast majority of the population, migrate between marine and fresh waters
Fecundity	The capacity of an individual or species to multiply rapidly; in a stricter sense, the number of eggs produced by an individual
Hermaphrodite	An organism with both male and female reproductive organs
Larvae	Independently living, post-embryonic stage of an animal that is markedly different in form from the adult and that undergoes metamorphosis into the adult form
Meridional	Running from pole to pole of a structure, as along a meridian
Omnivore	Animal that eats both plant and animal food
Pelagic	Living in the sea or ocean at middle or surface levels
Protandry	Condition of hermaphrodite plants and animals where male gametes mature and are shed before female gametes mature adj. protandrous
Telosyst	Group of fish including most modern bony fishes with thin bony scales covered by an epidermis, a homocercal tail, a hydrostatic air bladder, no spiracle and no spiral valve in the gut
Zonal	Moving perpendicular to the axis of a sphere; parallel to the equator

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CHAPTER 1: INTRODUCTION

"My own idea is that this fish is a saltwater fellow that breeds there, and makes up the rivers to stop there and grow fat and large. Being so large, his only real enemies in the brave old days were the crocodile and the aboriginal – not counting the droughts and floods…" F. Allen 1940, Rockhampton.

1.1 PREAMBLE

The climate of north-east Queensland is truly "a land of drought and flooding rain" (Dorothea Mackellar, 1861), a variability that is driven by a complex mix of climate systems including the monsoon, seasonal oscillations in the mid latitudes, intra-annual fluctuations of the Madden Julian Oscillation and inter-annual fluctuations of the Southern Oscillation as well as decadal and longer cycles. The implications of this variability in the climate for terrestrial production systems have been examined for a number of years (Meinke and Hochman 2000; Meinke and Stone 2004; Stone 1994). However, little research has been done to link climate variability and inshore fisheries. The barramundi is a high value fin-fish species distributed across much of the tropical developing world where it supports commercial, recreational and indigenous fishers and so provides an income and food supply for many. Its life cycle, although well understood, is also complex. A protandrous hermaphrodite, it inhabits both marine and freshwater ecosystems and changes from male to female over the years of development. Catch from one year to the next is reported to be highly variable in many areas. However, the possible effects of climate variability on the barramundi have not been examined in detail, and the impacts of climate change are as yet only hypothesised. This thesis brings together the disciplines of climatology and fisheries research to determine what aspects of the climate affect the catch of wild barramundi in north-east Queensland. The research also provides a methodology for examining similar relationships between the climate and other inshore fin-fish species.

1.2 RATIONALE FOR THIS RESEARCH

The wild fisheries of Australia, like those overseas, are under increasing threat from the pressures of over-fishing, habitat destruction and water quality degradation. In addition, inshore fisheries dependent on freshwater flows to provide nutrient pulses and nursery habitats are also affected by the natural variability in climate and the resultant flow regimes (Robins, Halliday *et al.* 2005). Since the El Niño events of the 1980s there has been extensive research into the large-scale climate mechanisms that create Australia's weather (e.g. Allan 2000), and the link between climate parameters and a range of fin-fish species has been examined in other regions of the world. Long-term Pacific oceanographic cycles have been shown to affect migratory fish such as sardines and herring (e.g. Klyashtorin 1998), and river flow has been shown to impact on estuarine species in a number of countries (e.g. Gunter and Hilderbrand 1954; Lloret, Lleonart *et al.* 2001; Sutcliffe Jr 1973). However, research that has linked climate parameters and inshore fisheries in Australia is limited.

The barramundi (*Lates calcarifer*) is an important commercial and recreational fish species in Australia currently worth approximately $9 million in commercial revenue alone (ABARE 2006). Commercial production displays a high degree of interannual variation and has ranged from 934 tonnes (live weight) in 1979/80 (Gray and Spencer 1986) up to 1061 tonnes in the 1995/96 financial year. However, similar to the Northern Territory (Griffin and Kelly 2001) and Gulf of Carpentaria fisheries, the north-east Queensland fishery has exhibited a decline in catch since the 1960s (Midgley 1987; Williams 1997). The downward trend in catch in many areas has been attributed to anthropogenic pressures including habitat degradation, impediments to water flow, pollution, the introduction of feral species, and/or over-fishing (Midgley 1987). Existing management strategies address the two major threats of habitat degradation (by protecting fish habitat areas and creating marine national parks and "green zones" where fish cannot be caught), and excessive fishing pressure (by enforcing bag limits, licence requirements, size restrictions and seasonal closure) (Q.F.M.A. 1994). However, despite a common saying used by many fishers that "a drought on the land means a drought at sea", limited research has been undertaken to determine if natural variability in the climate is a driver of the variation in barramundi catch. In addition, results to date vary both spatially and temporally perhaps as a result of the limited number of climate mechanisms considered, fishery responses to unidentified climate thresholds (IRI 2001), different time periods and locations of the work or anthropogenic climate change (Hobday and Matear 2006). Further, these results may also be affected by anthropogenic factors that have not yet been clearly identified (Cappo, Alongi *et al.* 1998; LWA 2005). Finally, current guidelines for harvest do not consider how climate variability affects catch or what impacts climate change may have on the fishery in the future.

1.3 RESEARCH AIMS

This study addressed the above gaps in knowledge by examining the impacts from both long-term and short-term climate variability, climate threshold events, climate change and other anthropogenic influences on the commercial barramundi fishery of north-east Queensland. The study had six specific objectives:

1. To determine if intra-annual climate variability as measured by seasonal records of rainfall, temperature, freshwater flows, evaporation, sea surface temperatures (SSTs) and indices of the Madden Julian Oscillation (MJO) and El Niño / Southern Oscillation (SOI) impact on the commercial catch of wild barramundi in the Princess Charlotte Bay area, a near-pristine environment.

2. To determine if anthropogenic changes to habitat have altered or masked the relationships between intra-annual climate variability and commercial catch of wild barramundi in the Fitzroy River area, an anthropogenically modified environment.

3. To determine if there are non-linear relationships between short-term climate variables and commercial catch of wild barramundi in Princess Charlotte Bay and, if so, to quantify the hydrometeorological thresholds or extreme events affecting the fishery.

4. To examine the impact of inter-annual climate variability from large-scale, long-term climate oscillations as measured by indices of the Interdecadal Pacific Oscillation (IPO), Southern Annular Mode (SAM), Quasi-biennial Oscillation

(QBO) and sub-tropical ridge cycles (*L*-index) on the commercial catch of wild barramundi across north-east Queensland from Cairns south to Bundaberg.

5. To develop a statistical model to predict commercial barramundi catch in Princess Charlotte Bay using climate parameters.

6. To examine the likely impacts of climate change on the long-term productivity of the commercial barramundi fishery in Princess Charlotte Bay.

1.4 THESIS STRUCTURE AND OUTLINE

Chapter 2 is a review of research from both overseas and within Australia that has examined the effects of climate variability on wild fin-fish, with particular focus on the barramundi fishery of Australia. **Chapter 3** presents the underpinning conceptual model, hypotheses and methodology developed in undertaking the study. **Chapters 4** and **5** detail the analysis of short-term climate effects on commercial barramundi catch in the near pristine Princess Charlotte Bay and the anthropogenically modified Fitzroy River area respectively. **Chapter 6** examines the consequences of non-linear and extreme or threshold climatic events on the barramundi fishery in Princess Charlotte Bay and **Chapter 7** examines how large-scale, long-term climate cycles influence wild barramundi catch across the whole of north-east Queensland. **Chapter 8** describes the development of a statistical model to predict commercial barramundi catch in Princess Charlotte Bay, and the future impacts of anthropogenic climate change on this fishery are examined in **Chapter 9. Chapter 10** provides a synthesis of the study, summarises the main findings, and makes recommendations for future research and possible improvements to the management of the north-east Queensland barramundi fishery (Figure 1.1).

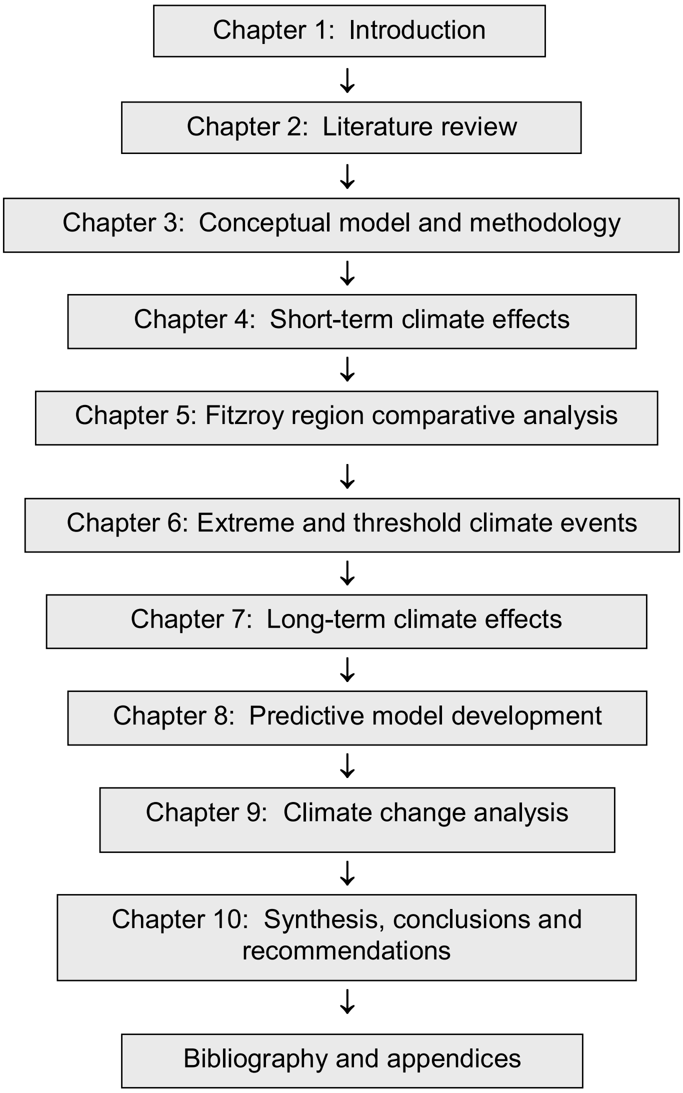


Figure 1.1 Flow chart outlining the structure of the thesis and chapter content.

CHAPTER 2: A REVIEW OF THE EFFECTS OF CLIMATE VARIABILITY ON WILD FISHERIES

When the wind is in the north
The skillful fisherman goes not forth;
When the wind is in the east,
'Tis good for neither man nor beast.
When the wind is in the south,
It blows the bait from the fishes' mouth;
When the wind is from the west,
Fishing's at its best.

Izaak Walton, 1593- 1683

2.1 INTRODUCTION

The term ‘climate’ was defined by Oliver (1981) as “the aggregate of weather at a given location for a given time period”, the first study of which is attributed to Hippocrates in his treatise Airs, Waters and Places (c. 400 BC). In contrast, weather is defined as the “physical condition of the Earth’s atmosphere (particularly the troposphere) at a specific time and place with regard to wind, temperature, cloud cover, fog and precipitation” (Lawrence, Jackson *et al.* 1998). Quantifiable statistical studies of a link between the climate and variations in commercial fishery catch were first undertaken by Hjort (1926) who demonstrated that environmental conditions, and not migrations, were responsible for the variability in Norwegian herring and cod catches. Much of the subsequent research focussed on the link between climate variability and the responses from large pelagic fisheries such as Peruvian anchovy, Icelandic herring and Norwegian herring and cod. Overall, these studies have indicated that changes in sea surface temperatures (SSTs), ocean currents, and long-term oceanographic and atmospheric circulations such as the Interdecadal Pacific Oscillation (IPO) and El Niño Southern Oscillation (ENSO) can have significant and varied impacts on fish catch.

The IPO (Power, Tseitkin *et al.* 1999) also known in the north Pacific as the Pacific Decadal Oscillation (PDO) (Mantua, Hare *et al.* 1997), is a multi-decadal atmospheric and oceanic cycle that consists of a horseshoe pattern of anomalous SSTs in the tropical western Pacific Ocean that extends to the north-west and south-east subtropics in a near symmetric pattern about the meteorological equator (Folland, Parker *et al.* 1998; Mestas-Nuñeza and Miller 2006). IPO ‘events’ are most visible in the North Pacific and persist for 20 – 30 years. Abrupt regime shifts have occurred in 1925, 1947 and 1977 (Aita, Yamanakaa *et al.* 2005; Mantua and Hare 2002). These events closely resemble the signal generated by ENSO (Zhang, Wallace *et al.* 1997) and some argue are forced by ENSO (e.g. Newman, Compo *et al.* 2003). Other researchers (e.g. Latif, Kleeman *et al.* 1997) argue the IPO is distinct from ENSO as it is not linked to SSTs in the critical ENSO regions of the eastern equatorial Pacific.

Multi-decadal changes in climatic and oceanographic conditions (such as those driven by the IPO) have been shown to generate long-term changes in primary production and phytoplankton biomass. Simultaneous oscillations in catch have occurred in affected Atlantic and Pacific herring, Atlantic cod, European, South American, Peruvian, Japanese and Californian sardine, South African and Peruvian anchovy, Pacific salmon, Alaskan pollock and Chilean jack mackerel (Aita, Yamanakaa *et al.* 2005; Beamish, McFarlane *et al.* 1999; Beamish, Noakes *et al.* 1999; Hare and Mantua 2000; Klyashtorin 1998; Klyashtorin 2001). In fact, it is now proposed that the whole ecosystem balance of the Pacific Basin oscillates between an “anchovy regime” and a “sardine regime” every 50 years or so in response to these multi-decadal climate cycles, a phenomena that appears to have occurred for hundreds of years (Chavez, Ryan *et al.* 2003; Sandweiss, Maasch *et al.* 2004).

At the short-term scale, the link between climate and fisheries has been known to the Peruvian fishermen for centuries as it was they who named those years of poor anchovy catch as a result of unusually warm water off the west coast of South America ‘El Niño’. ENSO is a complex ocean-atmosphere system second only to the seasons in generating large-scale variability within the climate (e.g. Allan 1988; Sturman and Tapper 2006) and is responsible for up to 40% of the rainfall variability in eastern Australia (Cordery 1998). In the ENSO neutral state, the atmospheric circulation consists of an area of low pressure and ascending air in the western Pacific, upper level westerlies, a region of descending air in the eastern Pacific, and low level easterly winds (Figure 2.1). The surface winds push warm surface water along the equator to the western equatorial Pacific, and leave an area of cool SSTs augmented by upwelling in the eastern equatorial Pacific (Graham and White 1988).

During a La Niña event this atmospheric circulation is enhanced and produces stronger than average low level easterly winds and an increased probability of above average rainfall across northern and eastern parts of Australia, Indonesia and other western Pacific regions. The other extreme of the Southern Oscillation, El Niño, is characterised by a migration of warm SSTs eastward along the equator and associated atmospheric changes. During an El Niño event, warm, moist air rises in the east, and cooler, drier air descends over the western Pacific. The Trade Winds (that normally blow from the south-east in the southern hemisphere) slacken and may revert to westerlies, and upper level winds blow towards the east. Rainfall across northern and eastern Australia tends to be below average and there is an increased probability of drought (e.g. Allan 1988). El Niño events typically occur every 2 – 7 years, during which the monsoon trough is weakened and displaced further north and maximum rainfall and peak freshwater flows in north-east Queensland occur slightly earlier than average (Evans and Allan 1992; Lough 2001; McBride 1987). In the southern hemisphere, the effects from ENSO are strongest and most spatially coherent in winter and spring, and weaker in summer and autumn (Lau and Nath 2000; McBride and Nicholls 1983; Nicholls and Kariko 1993; Simmonds and Hope 1997; Zhang and Casey 1992).

ENSO has been shown to reduce the catch of anchovy, mackerel, sardines, hake and shrimp in the eastern Pacific due to dramatic reductions in primary production (Barber and Chavez 1983; Castro and Hernandez 2000; Castro, Salinas *et al.* 2000). Similar responses have been observed in inshore areas too (e.g. the Gulf of California), where pelagic ecosystems (as measured by zooplankton biomass, larval abundance and distribution) differ significantly between an El Niño and La Niña event (Sánchez-Velasco, Avalos-García *et al.* 2004; Sanchez-Velasco, Valdez-Holguin *et al.* 2002).

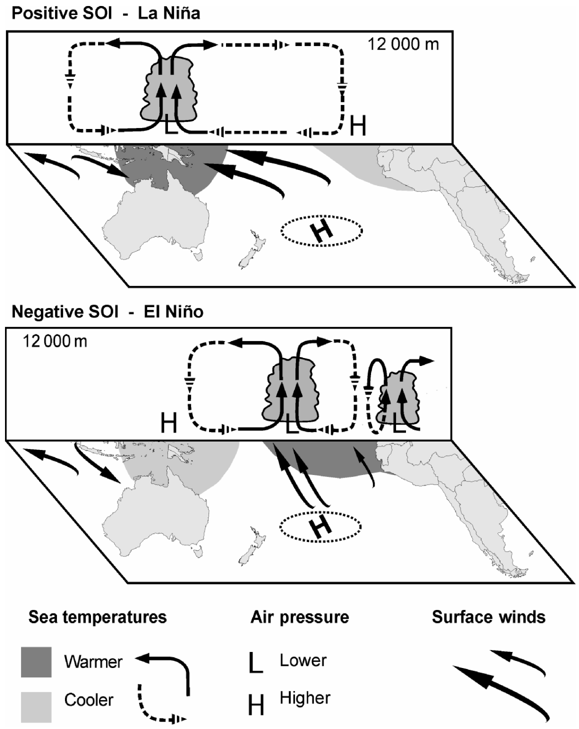


Figure 2.1 The two extremes of ENSO. During El Niño events the Southern Oscillation Index (SOI) is negative, anomalously warm water and increased convection is centred over the central equatorial Pacific and often results in anomalously cool water and subsidence over the western Pacific and northern Australia. This pattern is near reversed in La Niña years (Clewett, Clarkson *et al.* 1994).

2.2 OVERSEAS RESEARCH

Other studies of oceanic pelagic fisheries are reviewed in more detail elsewhere (e.g. Bell and Pruter 1958; Glantz and Feingold 1990). Instead, this review focuses on a selection of overseas and Australian studies that examine the impact of a range of climate variables on inshore and estuarine fin-fish species (see Appendix 1 for a summary of key findings).

SSTs and long-term climate variability and ENSO

As is the case with offshore fisheries, changes to water temperature can either increase or decrease the catch of inshore fisheries depending on species. An early analysis of inshore commercial fish and shellfish species including Atlantic cod and herring, redfish, butterfish, alewife, hake, bass, flounder, clams and scallops (Sutcliffe Jr, Drinkwater *et al.* 1976) found that the catch of ten species significantly correlated with

SSTs in the Gulf of Maine (USA) at various time lags. In some cases, the monthly average SST explained up to 76% of the variability in landings but species response differed. For example, the New England catch of sea scallops (*Plactopecten magellanicus*) was positively correlated with St Andrews SSTs (1928 – 1971) in November six years before catch ($r = 0.796$), while the landings of soft shelled clams (*Mya arenaria*) for the same area and period were negatively correlated with St Andrews SSTs in November and December seven years before catch ($r = -0.798$). For the anadromous Alewife (*Alosa pseudoharengus*), April SSTs explained 72% of catch six years later. Anadromous species utilise both fresh and marine habitats during their life cycle, spawning in freshwater and migrating to the ocean to mature. Thus, they are similar to the catadromous barramundi that spawn in the estuary and migrate to freshwater environments to mature.

At the multi-centennial scale, the analysis of 2 200 years of lake sediments showed that climate was the cause of coherent changes in the population of another anadromous species, the Sockeye salmon (*Oncorhynchus nerka*), across large geographic areas of Alaska (Finney, Gregory-Eaves *et al.* 2002). These changes are much greater than those seen at the inter-decadal scale and may reflect major changes in the ocean-atmosphere circulations in the north-eastern Pacific. Dramatic decreases in salmon abundance around 100 BC coincided with increased SSTs in the Santa Barbara basin, while increases after approximately 1200 AD corresponded to a period of glacial advances in southern Alaska and the Canadian Rockies.

More recent variations in salmon catch (Chinook, Sockeye and Pink salmon) in Oregon, California, Alaska and Washington were attributed to regime shifts in the IPO (Mantua, Hare *et al.* 1997). Changes in coastal sea and continental air surface temperatures, air pressure, rainfall and stream flow altered mean salmon catch by –64.4% to + 251%. However, such changes in catch may not be driven by direct changes in the climate, but by more complex interactions. A study of the survival of juvenile Coho salmon (*Oncorhynchus kisutch*) in Oregon and Washington, for example, showed that rather than environmental conditions directly affecting the food supply, reduced survival was due to higher levels of predation when earlier decreases in primary production in the marine environment followed a reduction in upwelling (Fisher and Pearcy 1988).

Such complex species associations and resultant changes in productivity were demonstrated in a thirteen year study carried out in the Apalachicola River estuary in Florida by Livingstone (1997) during which time a drought occurred. In the first year of the drought, light penetration into the water column increased, thereby increasing primary productivity and resulting in an increase in herbivore and omnivore abundance. As the drought progressed, however, severe decreases in nutrient levels and freshwater flow resulted in a decrease in primary production along with a corresponding decrease in dependent species numbers further up the food web, and eventually carnivorous predators. Overall, species diversity decreased during the drought period and increased with periods of high river flow. These studies illustrate that climate can affect inshore and estuarine fisheries such as barramundi and salmon through both oceanic (upwelling, currents, SST) and terrestrial effects (water flow, sediment, rainfall and temperature).

Rainfall and freshwater flows

One of the first studies to consider the effect of rainfall and subsequent freshwater flows on the commercial catch of an estuarine dependent species focussed on the white shrimp (*Penaeus setiferus*) off the coast of Texas (Gunter and Hilderbrand 1954). The shrimp spawns in the open sea and moves into the estuary to mature, later returning to the sea to breed. The authors proposed that increased rainfall reduced the salinity in the estuary, which in turn increased the size of the maturing shrimp and the subsequent catch. In Mozambique, increased outflow from the Zambezi River increased recruitment strength of the shallow-water shrimp (*Penaeus indicus*) by affecting either the number or size of recruits (or a combination of both) (Jorge da Silva 1986). And in Canada, monthly river flow showed a significant positive correlation with total annual halibut (*Hippoglossus hippoglossus*) catch at a lag that corresponded with species growth to maturity (Sutcliffe Jr 1973).

However, the biological responses from a fishery to climatic conditions such as flow are often complex and not necessarily the same, even for similar species. For example, research in the Gulf of Mexico on shrimp returned mixed results (White and Downton 1991). Spring and winter river discharge was the most important variable in the summer landings of brown shrimp (*Penaeus setiferus*) but other variables including air and sea surface temperatures, rainfall and wind stress gave no consistent relationship with landings. Landings of white shrimp (*Penaeus sztecus*), on the other hand, were positively correlated with summer SSTs and river discharge and negatively correlated with SSTs, air temperatures and wind vectors in winter. Such results highlight the importance of understanding the species' life cycle to ensure there is a causal link between changes in a climate variable and subsequent fisheries catch. This concept was demonstrated by Sheridan (1996) who developed a range of linear regression models to predict pink shrimp (*Penaeus duorarum*) landings. The best of these models contained environmental factors that were known to affect survival, growth and recruitment of juvenile shrimp in the nursery and adjoining coastal habitats (including freshwater flows) and explained 91% of variability in catch.

Other climate variables

Other climate variables such as wind speed and direction have also been shown to significantly affect reproductive success, early life-stage survival, and subsequent increases in fisheries catch. In the north-west Mediterranean, conditions conducive to planktonic production and retention of fish larvae, as a result of freshwater flows and wind mixing during the spawning season, had a significant positive correlation with the subsequent catch of 13 different commercial species (Lloret, Lleonart *et al.* 2001). Increased productivity of the spawning and nursery grounds following the heavy rains of an El Niño resulted in high densities of anchovies eggs and larvae in ocean areas affected by Yangtze River outflow (Kim, Kang *et al.* 2005). In Canada, a combination of changes to salinity from freshwater flow, and coastal SSTs at the time of spawning, explained 65% of the subsequent variability in cod (*Gadus morhua*) landings (Drinkwater and Myers 1987), while the annual landings of sole (*Solea solea*) were found to correlate positively with annual flow from the Rhone River five years earlier (Salen-Picard, Darnaude *et al.* 2002); a result again explained by long-term increases in food supply after flood events.

These studies demonstrate that the relationships between fishery productivity and climate variables are both diverse and complex. Survival and reproductive success depends on both the life cycle of the fish and its ecosystem. However, it can be surmised that increased catch is often the result of climate mechanisms that contribute to the creation of optimum spawning/nursery habitats or enhanced primary production and hence food supply. But do these finding apply to the Australian environment where climate variability is higher than for other regions of the world?

2.3 AUSTRALIAN RESEARCH

The geographical spread of studies that have examined the effects of climate variability on fisheries in the Australian region is shown in Figure 2.2 (details of key findings in Appendix 2). These studies represent 23 species (both inshore and oceanic) and ten climatic variables. Those studies that consider the impact of climate on fin-fish are reviewed here in more detail.

SSTs and ENSO

Unique to north-west Australia, the Leeuwin Current (width 20 km) flows southwards from Indonesia along the Western Australian coastline between April and July at a rate of up to 4 $km.h^{-1}$ (Cappo, Alongi *et al.* 1998; Pearce 1988). Water in the Current is typically $2^{o}C$ warmer and less saline than the local water. The strength of the Current, resulting mean sea level heights and SSTs vary in response to ENSO. Relative to average, weaker flows are associated with El Niño events and stronger flows with La Niña conditions (Meyers 1996). These changes along the West Australian coast have been shown to affect a number of species including the western rock lobster (*Panulirus cygnus*) (Caputi and Brown 1993; Caputi, Chubb *et al.* 1993; Caputi, Chubb *et al.* 2001; Caputi, Fletcher *et al.* 1996; Pearce 1988) and the saucer scallop (*Amusium balloti*) (Caputi, Fletcher *et al.* 1996; Caputi, Penn *et al.* 1998; Joll and Caputi 1995; Lenanton, Joll *et al.* 1991). For fin-fish species, the Leeuwin Current significantly reduces the production of Western Australian pilchard (*Sardinops sagax neopilchardus*) in the Albany region during years when the current is strong (Lenanton, Joll *et al.* 1991), probably as a result of changes in the advection and transport of eggs and larvae (Caputi, Fletcher *et al.* 1996; Fletcher, Tregonning *et al.* 1994). In contrast, the Australian salmon (*Arripis truttaceus*), whitebait (*Hyperplphus vittatu*) and Australian herring (*Arripis geogianus*) show a significant positive correlation between recruitment and the strength of the Current in the Great Australian Bight and along the South Australian and Victorian coastlines (Caputi, Fletcher *et al.* 1996; Lenanton, Joll *et al.* 1991). Increased recruitment in these species is most likely a result of larval transport to suitable nursery habitats, increased recruitment success, or positive effects from altered SST regimes on the life cycle stages of each species.

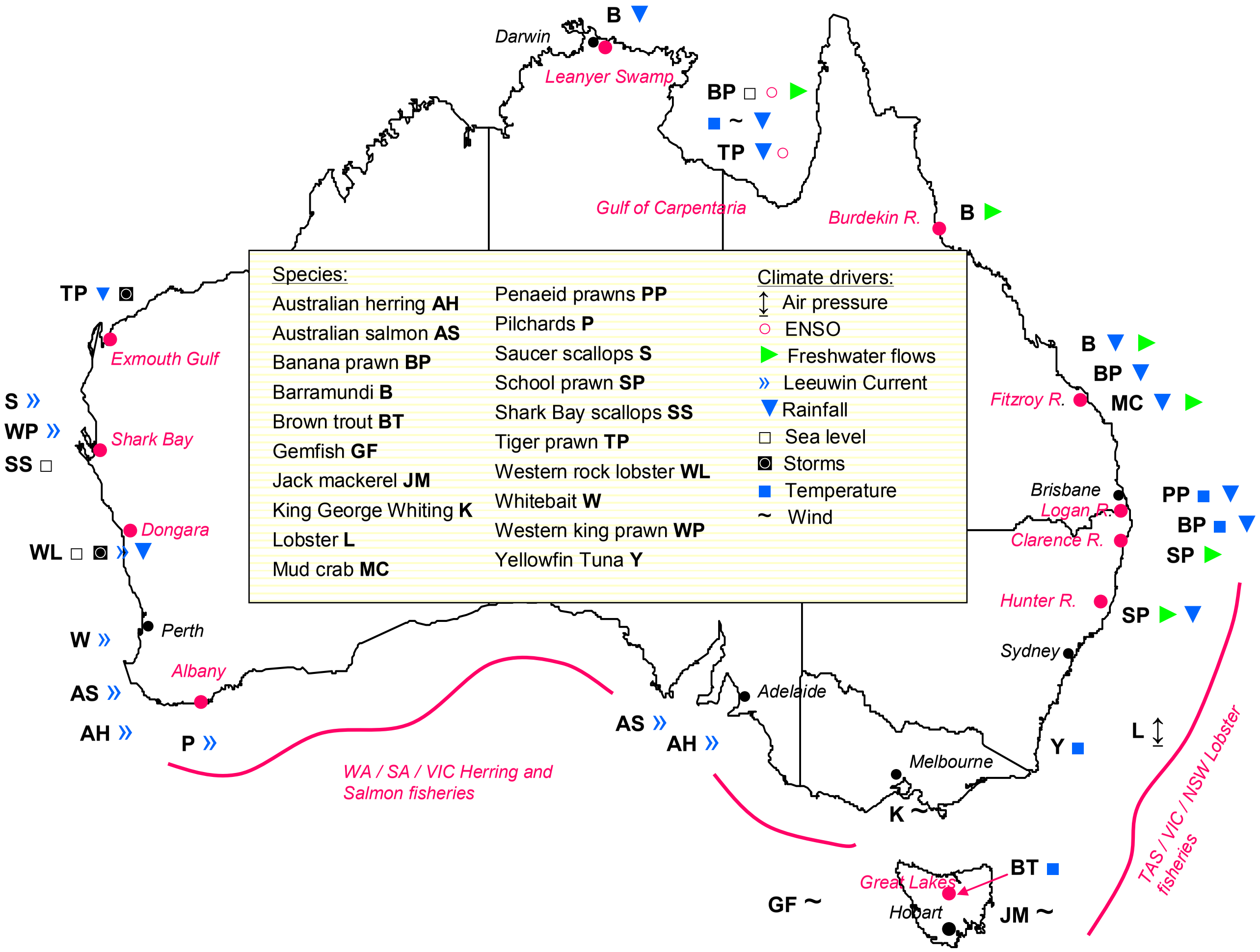


Figure 2.2 Location of studies linking climate and fisheries in Australia. Species researched are indicated by letter and climate parameters by symbols as shown in key. Key findings for each species are summarised in Appendix 2.

While Tasmania lies beyond the influence of the Leeuwin Current, the latitude of the sub-tropical ridge (LSTR) is also affected by ENSO, which in turn alters SSTs in the Tasman Sea and rainfall across the Australian continent. The LSTR, or southern hemisphere anticyclone (high pressure) belt, affects latitudes from 35^{o}S – 60^{o}S and oscillates latitudinally to an approximate 11 year cycle (Allan 1991; Harris, Davies *et al.* 1988; Pittock 1973), possibly driven by the solar sun-spot cycle (Labitzke 2004; Thresher 2002). When the sub-tropical ridge tracks further north, conditions across the Australian continent are drier, with weaker southerlies in the winter and stronger southerlies in the summer months, which offset the rain bearing Southern Ocean and monsoonal moisture sources (1910s – 1950s). The reverse is true when the sub-tropical ridge tracks further south and creates stronger southerlies through the winter months, and stronger northerlies in the summer months, which channel moisture over the continent (1860s – 1910s and 1950s – 1970s) (Allan 1991). The ridge is generally stronger and located further equatorward during an El Niño event and weaker and further poleward during a La Niña (Drosdowsky 2005).

Changes in the LSTR also affect the circum-Antarctic zonal westerly winds over south-eastern Australia. Strong circum-Antarctic zonal westerly winds force an overturning of the water column in the Tasman Sea, and result in the advection of cold, nutrient-rich subantarctic waters and changes in nitrate concentrations and SSTs (Harris, Griffiths *et al.* 1992). Under these conditions, the algal spring bloom can occur up to three months later in the year but is stronger when it does occur and so affects the entire food chain in the region. The catch and distribution of southern blue-fin tuna (*Thunnus maccoyii*), barracouta (*Thyrsites atum*) and jack mackerel (*Trachurus declivis*) (Harris, Griffiths *et al.* 1992) are subsequently influenced. In contrast, yellow fin tuna (*Thunnus albacares*) off southern New South Wales, appear to be attracted to a warm-core eddy at the edge of the continental shelf. However, as in the colder waters of the Tasman Sea, water samples showed significantly higher concentrations of zooplankton and micronekton than in the surrounding waters (Young, Bradford *et al.* 2001).

Rainfall and freshwater flows

ENSO and other long-term climate oscillations produce highly variable rainfall across Australia and consequent high variability in freshwater flows. This variability affects the physical, chemical and biological processes of the fisheries habitat by modifying salinity and oxygen levels, introducing organic matter, sediment and nutrients and changing water temperatures (Drinkwater and Frank 1994). Most Australian studies that have investigated the relationship between fisheries and freshwater flow and/or rainfall consider prawns or shrimp and have been recently reviewed by Robins, Halliday *et al.* (2005). A review of coastal and estuarine fin-fish (Loneragan and Bunn 1999) concluded that freshwater flows have a "strong positive effect on the production of commercial and recreational coastal fisheries" and that the seasonality of flow is as important as magnitude. This conclusion has been supported by a more recent study on the Campaspe River in Victoria that showed reduced freshwater flows prevented spawning of native freshwater fish due, most probably, to unfavourable hydrology, habitat and food (Humphries, Lake *et al.* 2001). Along the coast of Queensland too, the occurrence of El Niño events and prolonged dry periods corresponded with reduced catch for mullet (*Mugil cephalus*) and flathead (*Platycephalus spp*.) (Meynecke, Lee *et al.* 2006).

Wind

Wind strength across the Australian continent is affected by a number of climate systems including ENSO and the LSTR as discussed earlier. Increases in zonal westerly winds across Tasmania increase the incidence of cold, wet weather and decrease the temperature in the Great Lakes. Such conditions have been shown to both increase the proportion of brown trout (*Salmo trutta fario*) at first spawning (three year olds), and alter the migrations of spawning female trout (Harris, Davies *et al.* 1988). Increased zonal westerly wind strength also had a significant and positive correlation with the catch of King George whiting (*Sillaginodes punctata*) in Victoria three to five years later (Jenkins 2005). Most likely the winds improved survival and transport of larval and post-larval stages of the fish, or perhaps increased the production of plankton that the larvae feed on in bays along the coast.

Gemfish (*Rexea solandri*) recruitment off the south-east coast of Australia also shows statistically significant positive correlations with zonal westerly wind strength (Thresher 1994), although, how the wind strength affects recruitment for this species was not reported. Finally, at Lizard Island on the Great Barrier Reef, inter-annual changes in wind stress (specifically onshore winds) varied the supply of larvae to various locations around the island for three families of reef fish (Milicich 1994).

Other climate variables

Drought is a regular occurrence in Australia and is often associated with El Niño events. The 2001 – 2003 drought across Australia coincided with the collapse of the southern Gulf of Carpentaria mud crab fishery and Weipa banana prawn fishery, and changed the migratory patterns and catchability of grey mackerel (*Scomberomorus semifasciatus*) (Gribble, Rasheed *et al.* 2005). These responses are probably the result of both direct and indirect cascade effects through the ecosystem, such as changes in freshwater flow, the extent of sea grass beds and changes in coastal primary production. The complexity of these interactions requires further examination (Gribble, Rasheed *et al.* 2005).

Extreme or threshold climatic events such as tropical cyclones, intense storms and tidal surges also impact dramatically on the marine and estuarine environment by shifting sand and sediment, changing river courses, inundating freshwater areas with saline intrusions, uprooting kelp and sea grass beds and damaging coral reefs (Cappo, Alongi *et al.* 1998). Some of these changes are long-lived and have repercussions up the food chain. However, there are no studies of Australian fisheries that consider these events in any detail.

In summary, Australian inshore fin-fish are, like their overseas counterparts, affected in various ways (depending on species) by seasonal, inter-annual and long-term variations in the climate including changes to SSTs, freshwater flows, rainfall, wind, air temperature and extreme or threshold events such as drought. However, most studies only consider a limited number for climate variables on a single fishery over a short period of time. In addition, the studies represent a limited number of locations around the Australian coastline, and only a relatively small proportion of Australia's 420 commercial fish species (CSIRO 2006b), although, certainly, some of the largest and most valuable fisheries are included. Few studies take the next step to explore the spatial and temporal impacts of climate variability on a fishery by considering a number of climate parameters or by comparing results from different locations or at different time scales. A lack of fisheries catch data and species life cycle knowledge is often a limitation, as is the complexity of ecosystem-scale climate interactions. Indeed, teasing apart the many and varied influences of changes to habitat, fishing pressure, freshwater flow, sediment transport and ecosystem response is no easy task. However, an understanding of the proportion of fluctuation in fisheries biomass as a result of natural climate variability is essential in order to accurately quantify the likely impact future climate change may have on a fishery. As recommended by Cappo, Alongi *et al.* (1998) future research on fisheries requires a more integrative, ecosystem focus that includes an understanding of the underlying natural dynamics and environmental variability of the fishery: an essential step in order to distinguish between natural and anthropogenic impacts on fishery habitats and catch.

2.4 THE BARRAMUNDI AND IMPACTS FROM CLIMATE

The barramundi

The barramundi (*Lates calcarifer*) of the family Latidae is widely distributed across the tropical Indo-Pacific region including India, Bangladesh, Burma, the Malay Peninsular, Java, Sumatra, Borneo, Celebes, Sarawak, Phillipines, Papua New Guinea, northern and western Australia and southern China and Japan (Greenwood 1976). The name barramundi comes from the aboriginal word 'burramundi' meaning "large scales" (Schipp 1996), and is used to describe specimens in Australian waters. The species is known as 'amama' in Papua New Guinea, 'Asian seabass' in Indonesia and Thailand, and 'bhekti' in India (Fishbase 2005).

Over a lifespan of some 20 years, the barramundi can reach a length of 200 cm and weigh in excess of 70 kg (Fishbase 2005; Garrett 1992; Russell 1988). The fish has a typical perch shape, sharp spines on the sides of its head and is coloured bluish-grey to greenish-grey above, silvery on the sides and white below (Plate 2.1).

Plate 2.1 Adult barramundi (Photo courtesy of Fishbase website 2005).

Species distribution

Distribution of the barramundi is tropical, and in Australia ranges from the Noosa and Mary Rivers on the east coast (26^{o} 30'S), to the Ashburton River in Western Australia (22^{o} 30'S) (Dunstan 1959; Fishbase 2005; Morrissy 1985). As many as sixteen genetically discrete populations occur across northern Australia, separated by distances of less than 300 km in the west and up to more than 500 km along the east coast (Keenan 1992; Keenan 1994) (Figure 2.3). As tagging studies suggest that the migration distance of adults ranges from only 50 to 100 km, and there are few successful migrations along the coastline due to predators (e.g. Garrett and Russell 1982; Keenan 1992; Keenan 1994; Russell 1988; Russell and Garrett 1988; Shaklee, Salini *et al.* 1993), genetic homogeneity at distances greater than 100 km is most likely due to the dispersion of larvae and juveniles during major river flood events (Keenan 1994). Generally, populations are isolated by highly saline water as individuals prefer brackish and estuarine tidal areas adjacent to fresh water where they remain close to the nursery habitats and fresh water river systems required for juvenile growth (Davis 1985; Dunstan 1959; Griffin 1987; Keenan 1994; Shaklee and Salini 1985; Shaklee, Salini *et al.* 1993). The variation in genetic make-up from one population to the next is congruent with evolution in a stepping-stone fashion (from one area to the next) as a result of individuals isolated by distance (Chenoweth, Hughes *et al.* 1998).

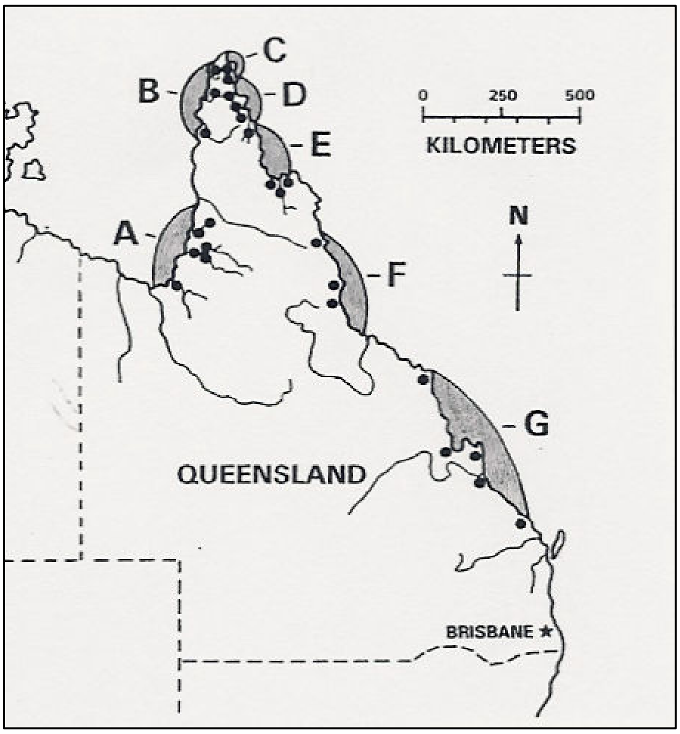


Figure 2.3 Map of Queensland, Australia showing the distribution of barramundi genetic stock. The population distribution for each group identified (A through G) is shown as a shaded area and population focal points are indicated by dots (Shaklee, Salini *et al.* 1993).

Habitat

In Australia, barramundi are found in coastal waters, estuaries, tidal creeks and lagoons, ponded pastures, supralittoral saltpans, flood plains and rivers in both clear and turbid water ranging in temperature from 15 – 39^{o}C (Coates and Unwin 1991; Davis 1985; Davis 1988; Dunstan 1959; Fishbase 2005; Russell and Garrett 1983; Russell and Garrett 1985; Russell and Garrett 1988). Although water temperature appears to limit overall distribution of the species, populations are absent in areas without permanently flowing rivers (Dunstan 1959; Grey 1986). As adults, barramundi prefer slow moving or still, muddy water up to 40 m in depth and ranging in salinity from 0 – 40 ppt (Dunstan 1959; Fishbase 2005). Adults are rarely found in fresh, flowing water although some have been found in landlocked coastal swamps and lagoons (Dunstan 1959; Rohan, Griffin *et al.* 1981) (Table 2.1).

Biology and life cycle

The barramundi is a biologically complex species. As a protandrous hermaphrodite it undergoes a sex reversal from male to female during its life cycle. Also catadromous, the fish spawns in marine waters and migrates upstream to fresh water to grow before returning to salt water to mature (Davis 1985; Moore 1979; Moore 1982; Moore and Reynolds 1982; Reynolds and Moore 1982; Rohan, Griffin *et al.* 1981) (Figure 2.4).

Spawning is a seasonal event triggered by a number of factors some of which are climate related, including water temperature (Davis 1985; Garrett, Mackinnon *et al.* 1987; Griffin 1987), freshwater flow (Davis 1981; Dunstan 1959; Moore 1982; Sawynok 1998) and day length (Griffin 1987). Considered one of the most fecund of all fishes, the barramundi is estimated to produce up to 2.3 million eggs per kilogram of body weight throughout its life (Davis 1984; Garrett 1992). Adults congregate to broadcast spawn near the mouth of a creek or river where salinity ranges from 10 ppt to 36 ppt (Davis 1985; Moore 1982; Russell 1988) and water temperature from 27°C to 33°C (Davis 1985; Fishbase 2005). Spawning can occur upstream as long as salinity levels are high enough (Davis 1985; MacKinnon 1986). The time of spawning varies from November – January on the east coast of Queensland (Russell 1988) through December – March in the Northern Territory to September – February in Western Australia, and coincides with the full or new moon and an incoming tide (Bardach and Santerre 1981; Fishbase 2005; Garrett, Mackinnon *et al.* 1987; MacKinnon 1986). It has been proposed that the spring spawning event is triggered by an influx of organic matter into the estuary (which exhibits a unique odour that the fish are capable of detecting) in response to run off from rainfall (Lake 1967; Moore 1982). However, a study of rainfall and annual flow in the Fitzroy region of central Queensland showed no evidence that early wet season (October – November) river flow triggered, or was otherwise related to the timing of spawning (Sawynok 1998).

Table 2.1 River classification and barramundi habitat as defined by Dunstan (1959).

River type	Stream characteristics	Fresh water flow	Presence of barramundi
Large, meandering river and large catchment	Muddy or sandy bottom	Sluggish, slow, continuous flow	Excellent barramundi environment
Short, deep straight rivers with small catchments	Falling over coastal ranges, rocky or sandy bottoms	Fast and continuous flowing	Very few barramundi in these rivers
Impermanent rivers/streams	Sandy or pebbly bottoms upstream with isolated waterholes downstream	Impermanent flow of water	Barramundi absent in the upper reaches and scarce in lower reaches
Minor Waterways	Muddy streams and swamps near the coast	Connection to the coastal waters in the wet season	Immature barramundi plentiful, excellent nursery habitat
Tidal creeks	Short, small waterways discharging into mangrove swamps	Minimal fresh water flow	Very few barramundi in these waterways

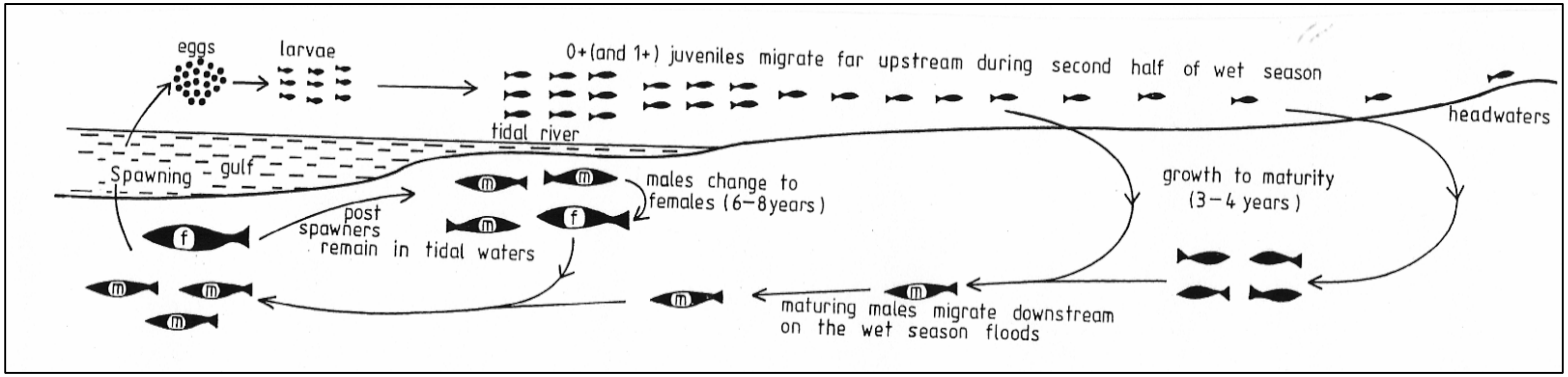


Figure 2.4 Diagram of the barramundi life cycle showing the significant stages and key habitats. “m” indicates male and “f” indicates females (Morrissy 1985).

It is now generally agreed that although the time of spawning varies from location to location, and year to year, the event is triggered by water temperature and other mechanisms that ensure juveniles have early access to inundated nursery areas where food supplies are abundant and competition low (Bardach and Santerre 1981; Davis 1985; Garrett 1986; Garrett, Mackinnon *et al.* 1987; Griffin 1995; Moore 1982). The long spawning season relative to other species is thought to be a result of the late arrival of landlocked fish to the spawning areas towards the peak of the wet season (Davis 1985; Dunstan 1959), or multiple spawning of individuals as appears to occur in Papua New Guinea and Thailand (Moore 1982). There are no records of reproductively mature individuals in landlocked freshwater (Dunstan 1959) and so barriers that prevent them reaching the marine environment would reduce the number of breeding pairs.

Barramundi eggs and larvae will only survive in water ranging in salinity from 22 to 40 ppt (Davis 1985; Garrett, Mackinnon *et al.* 1987; Moore 1982; Schipp 1996). Eggs hatch within 24 hours and post-larvae (approximately 10 – 15 mm in total length) move from the spawning areas to the sheltered, less disturbed tidal areas (De 1971) and then into nursery habitats of tidal pools, swamps, coastal plains and mangrove areas as fry (16 – 45 mm) and fingerlings (50 – 200 mm) (Davis 1985; De 1971; Dunstan 1959; Griffin 1985; Russell and Garrett 1985). Growth from spawning to fingerlings occurs over a period of about 26 days in high salinity environments where temperatures range from 26.5^{o}C to 32.0^{o}C (Fishbase 2005; Russell and Garrett 1985). Swamps provide refuge for post-larval and juvenile barramundi by providing an abundant food supply of other larval / juvenile fishes and crustaceans as well as protection from large piscivores. In areas of north-east Queensland without large river systems, coastal swamps were identified as the predominant nursery habitat for post-larval and juvenile barramundi before they moved upstream into tidal creeks and estuarine areas (Russell and Garrett 1985). Fingerlings have been recorded in salinities as high as 94 ppt and temperatures as high as 36°C (such as those in the Norman River estuary in northern Queensland), and as low as 16°C (Russell and Garrett 1983; Russell and Garrett 1985; Schipp 1996).

Juvenile barramundi follow the lower salinity environments upstream into coastal creeks and rivers. Early wet season rains, and an availability of coastal swamps, appear to significantly improve the survival rates of barramundi in the critical first few months (Davis 1985; Griffin 1985; Griffin 1986; Russell and Garrett 1983). Those juveniles arriving later in the season are predated upon by those spawned earlier, which might suggest that there is rarely an increase in year-class numbers as a result of landlocked adults spawning later in the season (Davis 1985). One exception may be if poor rains early in the season result in the nursery areas drying out, an event that would remove early spawned individuals from the habitat (Davis 1985). As the end of the wet season draws near, juveniles migrate into freshwater environments where they remain for a number of years until adult (Dunstan 1959; Griffin 1985; Russell and Garrett 1988).

The vast majority of maturing barramundi are initially male. Only a very small proportion, 9% of specimens in the 55 – 90 cm length range (Garrett 1992), are primary females (Moore 1979). Studies on barramundi in northern Australia show that males mature at 3 – 4 years of age at which time they measure 60 – 80 cm (Garrett 1992) and weigh between 2.6 – 4.2 kg (Grey 1986). Mature males migrate into local estuarine waters where they remain for one or more seasons before sex inversion occurs post-spawning (Davis 1982; Davis 1985; Davis 1986; Russell and Garrett 1985). By this stage the fish are usually 6 – 8 years of age and weigh 5 – 6 kg. Most fish in the 85 – 100 cm length range (7 – 12 kg) are females (Davis 1982; Garrett, Mackinnon *et al.* 1987; Moore 1979).

Growth of barramundi appears to be highest in the wet season when freshwater flow is greatest and water temperatures warmest (Davis and Kirkwood 1984; Sawynok 1998). The seasonal variation in growth rate enables fish to be aged by counting growth marks on their scales (Davis and Kirkwood 1984; Dunstan 1959), otolith bones, operculare bones, fin rays or vertebrae (Mishrigi 1966) in much the same way as tree rings. There is, however, difficulty in accurately gauging early years using any of these techniques and growth rates calculated using scales are not considered accurate after six years of age (Rohan, Griffin *et al.* 1981). Growth curves based on length and age from tagging studies vary between river systems (Davis and Kirkwood 1984; Dunstan 1959) but indicate that fish grow faster in the first and third years (Mishrigi 1966).

Feeding habits

In the larval stage (2.8 – 5.2 mm) barramundi are believed to be omnivorous but feed on insect larvae, crustaceans and other small fish once in the brackish nursery habitats (Davis 1984; Dunstan 1959; Moore 1982; Russell and Garrett 1985). By the juvenile stage, barramundi inhabit tidal creeks and are entirely carnivorous as they consume only fish and crustaceans (Davis 1984; Russell and Garrett 1985). Adults are voracious, predatory carnivores able to consume prey up to 50% their own weight/length, including younger barramundi (Davis 1984). This cannibalism can result in every second year-class having a higher level of predation than the one before (Griffin, Fisheries Biologist, Northern Territory Department of Primary Industries, pers. comm. June 2005) although this effect is reduced to some extent if young fish have access to extensive shallow nursery areas in their first few months (Moore 1982; Russell and Garrett 1983).

Impacts of climate on the barramundi

Table 2.2 summarises the effects of climate on barramundi as detailed in the studies reviewed.

Rainfall and freshwater flow

Successful recruitment of barramundi to adulthood and the commercial fishery appears to rely on a number of factors affected by freshwater flow and rainfall. These include the ability of adults to migrate between freshwater and marine environments for spawning, and the availability of both suitable estuarine conditions for a successful spawning event and nursery habitats for juvenile survival (Davis 1981; Dunstan 1959; Moore 1982; Reynolds and Moore 1973; Rozas and Hackney 1983; Sawynok 1998). In a number of studies, significant early wet season rains (October to December) have been shown to increase the survival rate of juveniles in the critical first few months after spawning by increasing the availability of coastal swamps and nursery areas (e.g. Davis 1985; Griffin 1985; Griffin 1986; Griffin 1995; Russell and Garrett 1983). The relationship between spawning season flow and long-term barramundi landings was shown to be significant in the Fitzroy River (Robins, Halliday *et al.* 2005) where summer flow and rainfall three years prior to catch explained 24% and 21% of the variability in landings, respectively. Further research in the Fitzroy concluded strongest recruitment occurred in years when freshwater flows were high in spring and summer, the time of year when fish are spawning and early life stages inhabit nursery environments (Staunton-Smith, Robins *et al.* 2004). However, too much flow may create unfavourable conditions for spawning as eggs and larvae will only survive in water of high salinity (Davis 1985; Garrett, Mackinnon *et al.* 1987; Moore 1982; Schipp

1996). Fingerlings too are attuned to changes in salinity, and follow freshwater signals at the end of the monsoon season to mature upstream (Russell and Garrett 1985).

In the Northern Territory, five years of sampling data from Bamboo Creek on the Daly River showed a significant positive relationship between early wet season rainfall and the abundance of juvenile barramundi (Griffin 1986). However, there was not a significant correlation between commercial catch of three or four year old fish and rainfall three to four years previously. This result suggests the increases in juvenile numbers did not carry through to the commercial fishery in this location. In the Gulf of Carpentaria, regression analysis identified rainfall as explaining up to 80% of the variation in barramundi catch (Meynecke, Lee *et al.* 2006). When included in the surplus production model CLIMPROD, rainfall and SOI improved the goodness of fit for barramundi catch on the Queensland east coast from an R^2 0.02 – 0.20 up to 0.30 – 0.87 depending on location. Seasonal correlations between barramundi catch and rainfall in the same year were higher than monthly relationships, which were also positive and significant for all Queensland regions tested.

Growth rates for individual barramundi, and therefore population biomass, also appear to be linked to freshwater flow. Both Robins, Halliday *et al.* (2006) and Sawynok (1998) found growth rates for barramundi in the Fitzroy River were positively correlated with freshwater flowing into the estuary, and Davis and Kirkwood (1984) determined growth rates of barramundi in five river systems in northern Australia was highest during the wet season.

In some cases, freshwater flow can increase the catchability of fish. Dunstan (1959) noted that the number of mature barramundi flushed into the commercial estuarine fishing areas increased after high wet season flows. This observation was confirmed in two studies, one by Platten (1999) who found recreational catch rates of barramundi were positively correlated with Boyne River outflow in Gladstone Harbour, and the other by Robins, Halliday *et al.* (2005) who identified a significant positive correlation between catch and summer flow in the year of catch.

Water temperature

Offshore currents and SSTs have a negligible influence on the shallow in-shore estuarine areas inhabited by the barramundi, although the distribution of the species is most probably determined by water temperature (Dunstan 1959). Growth of the fish is marginal in water temperatures below 22°C and severely curtailed below 20°C (Agcopra, Balston *et al.* 2005). Eggs are particularly sensitive to water temperature which affects both the time taken to hatch (Pauly and Pullin 1988) and survival (Garrett, Mackinnon *et al.* 1987).

In summation, consistent findings in the review include increased survival of barramundi eggs and larvae in high salinity environments (Davis 1985; Garrett, Mackinnon *et al.* 1987; Moore 1982; Schipp 1996), increased dispersal of eggs, larval stages and adults during extreme flood events (Keenan 1994; Kingsford and Suthers 1994), increased growth rates in years of high freshwater flows (Davis 1982; Robins, Mayer *et al.* 2006; Sawynok 1998), and an increase in barramundi landings in response to higher flows in the year of catch (Dunstan 1959; Platten 1996; Robins, Halliday *et al.* 2005). Other results are temporally and spatially variable: the relationship between early freshwater flow and spawning, catch and rainfall or freshwater flow at the time of early barramundi development, and the time required for growth to commercial size. These variations may be due to differences in the genetic make up of populations or changes in the ecosystem that have affected the fishery through complex species interactions. Differing results may also be an artefact of the limited number of studies undertaken in various locations and at various times.

In addition, other climate variables including shallow wetland water temperature, evaporation, and SSTs are not considered in previous studies and may influence recruitment of the species. Variations in climate driven by long-term climate systems such as the IPO have not been examined in any detail and apart from the observation that high flow events increase the growth and catchability of adults, the effects from other extreme or threshold climate events on the barramundi habitat have not been considered. Finally, the influences from anthropogenic changes to habitat have only received limited attention, and no studies to date have attempted to quantify the effects of climate change on the fishery.

This study aims to fill these gaps in previous research by addressing the following nine research questions:

1. What aspects of the barramundi life cycle are likely to be affected by climate?
2. Does short-term (inter-annual) climate variability have an impact on barramundi catch?
3. Is there a lag between the timing of climate impacts and subsequent barramundi catch?
4. Do anthropogenic impacts mask the effect of climate impacts on fisheries catch?
5. Do extreme events at the short-term time scale have a threshold or non-linear impact on barramundi catch?
6. Do long-term, large-scale climate oscillations impact on barramundi catch?
7. How much of the variability in barramundi catch can be predicted on the basis of climate variability?
8. What are the likely impacts of climate change on barramundi catch?
9. Can the management of the barramundi fishery be improved by including knowledge of the climate?

2.5 SUMMARY

Fisheries are impacted in various ways by numerous seasonal, inter-annual and longer-term variations in the climate including changes to SSTs, freshwater flows, rainfall, wind, air temperature and extreme or threshold events such as drought. The relationships between fisheries productivity and climate variables are both diverse and complex, depending on the life cycle of the fish, and interactions within the ecosystem that influence survival and reproductive success. Despite this, changes to the ecosystem that enhance primary production, extend suitable nursery habitats, or improve juvenile survival all appear to result in an increase in productivity, irrespective of species.

Only a limited number of studies have linked climate variability and the productivity of the barramundi fishery. Findings are consistent in that there is increased survival of eggs and larvae in high salinity environments, increased dispersal of eggs, larval stages and adults during extreme flood events, increased growth rates in years of high freshwater flows, and an increase in commercial catch in response to high flows in the year of catch. Results from studies of other aspects of the fishery such as the relationship between early freshwater flow and spawning have varied both spatially and temporally. No studies have examined climate variables other than rainfall, flow, water temperature and the SOI. The possibility of non-linear responses of the fishery as a result of an extreme event, or the likely repercussions of climate change on the long-term sustainability of the fishery, have not yet been examined. This study fills these gaps in knowledge by addressing nine research questions that focus on determining the impacts from a range of climate variables and extreme climatic events on the barramundi fishery of north-east Queensland. A comparative analysis of results at two locations determines the validity of transferring results from one location to another and quantifies the effect on the fishery from anthropogenic influences. A predictive model of barramundi catch is developed using only climate variables and, finally, the likely effects from anthropogenic climate change are examined.

Table 2.2 A summary of previous research linking climate variables with barramundi catch and recruitment in Australia.

Variable	Site	Study	Key Findings
Salinity	Various	Moore (1982); Davis (1985); Garrett, Mackinnon *et al.*(1987); Schipp (1996)	Survival of barramundi eggs and larvae reliant on high salinity water.
	GOC	Davis (1985)	The timing, intensity and duration of the wet season affects spawning success and juvenile survival.
Seasons	NT	Davis (1988)	Barramundi residency in the Leanyer swamp correlated with season.
Lunar cycle	Various	MacKinnon (1986); Garrett, Mackinnon *et al.* (1987)	Lunar cycles most probably the primary trigger mechanism for spawning in the species.
Rainfall	Various	Griffin (1985; 1986); Russell and Garrett (1983); Davis (1985)	Variations in wet season rainfall and resulting area of flooded, shallow, grassy floodplain nursery habitats, impact on survival of juvenile (8 – 200 mm) barramundi.
	NT	Griffin (1986)	Positive significant correlation between juvenile abundance and early wet season rainfall (r = 0.81) and CPUE and previous wet season rainfall (r = 0.69).
	NT	Griffin (1993)	Inclusion of rainfall in a Fox surplus production model improved prediction of barramundi catch.
	QLD	Robins, Halliday *et al.* (2005)	Summer rainfall 3 and 4 years prior to catch significantly correlated with long-term Fish Board landings.
	QLD	Meynecke, Lee *et al*. (2006)	In the Gulf of Carpentaria, rainfall explained up to 80% of the variation in barramundi catch. Seasonal correlations between barramundi catch and rainfall in the same year were positive, significant and higher than monthly relationships which were also positive and significant for all Queensland regions tested.
Freshwater flow	NT	Davis (1984)	Highest growth rates of barramundi during the wet season when fresh water flow was greatest.
	Various	Dunstan (1959); Reynolds and Moore (1973); Davis (1981); Moore (1982); Rozas and Hackney (1983)	Maturity and spawning of individuals was reliant on the availability of, and the ability to migrate between, freshwater and marine environments.
	Various	Lake (1967); Moore (1982)	Spawning may be triggered by an influx of organic matter (which exhibits a unique odour that the fish are capable of detection) into estuary as a result of run off from rainfall events.
	QLD	Robins, Halliday *et al.* (2006)	Growth rates of fish were significantly and positively correlated to freshwater flowing into the estuary.
	QLD	Staunton-Smith, Robins*. et al.* (2004)	Strongest year-classes associated with the wettest years when flows were highest, particularly in spring and summer when barramundi are spawning and juveniles inhabit nursery environments.
	QLD	Robins, Halliday *et al.* (2005)	Significant positive correlation between Fish Board landings and summer/autumn flow and summer rain 3 years prior to catch and summer flow and rain 4 years prior to catch. Significant correlation between CFISH logbook catch and summer flow and rainfall in the year of catch. 44% of variation in catch and year relationship residuals explained by a multiple regression model including annual flow, annual rain and autumn flow 2 years prior to catch.
	QLD	Sawynok (1998)	Positive correlation between recruitment, flows and October - February rainfall. Strong recruitment in years of high December – February flows (>1.4 Ml). Early October or November flows not related to spawning. Higher (lower) growth in high (low) flow rates. Greater movement of individuals during periods of high flow.

CHAPTER 3: METHODOLOGY

3.1 INTRODUCTION

The climate varies on time scales from inter-annual through to decadal and beyond and shows a high degree of spatial and temporal variability in the north-east Queensland region. Barramundi have a complex life cycle that involves habitation in both marine and freshwater environments and migration between the two, and numerous growth stages over a number of years. In order to understand the connections between the two, and answer the research questions posed in Chapter 2, a conceptual process model was developed to provide a simple structured methodology for the study. This chapter describes the underpinning rationale and logical steps followed in the development of the process model and addresses research question 1: What aspects of the barramundi life cycle are likely to be affected by climate?

3.2 METHODOLOGY

Understanding the effects of climate on a fishery requires first an understanding of the life cycle of the fish and secondly those stages of development that are likely to be affected by environmental conditions driven by the climate. Once these likely linkages are clear, a hypothesis of impacts from climate on the fishery as a whole can be developed. Testing this hypothesis requires data for catch (and preferably effort) and climate for a study area that has limited influences from other factors (such as anthropogenic changes to habitat, freshwater flow or species composition). Once the links between climate variables and fishery catch have been confirmed, it may be possible to predict using measures of climate what the future catch might be, and what effect anthropogenic changes (including global warming) may have on the fishery. These steps were incorporated into a process model that outlines the methodology used in the study (Figure 3.1).

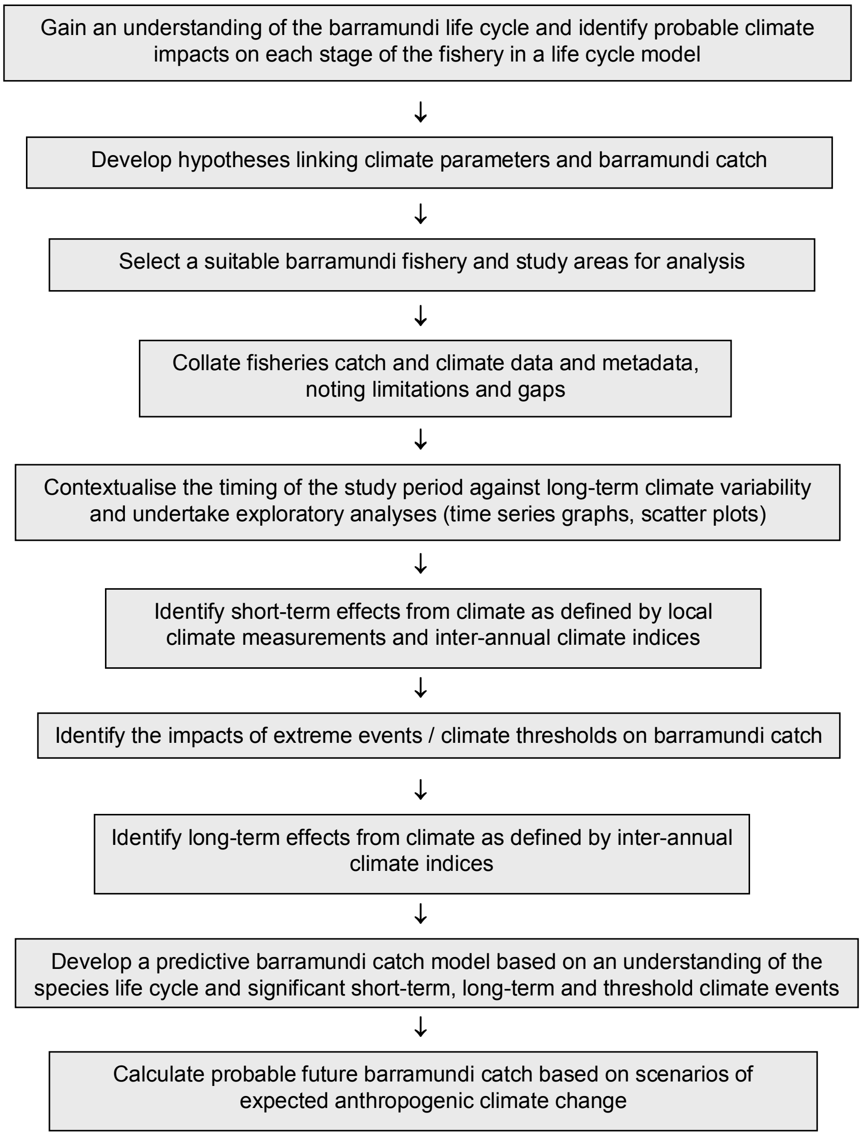


Figure 3.1 Conceptual process model developed for determination of the impacts of climate on the barramundi fishery of north-east Queensland.

Development of a barramundi life cycle model

An integrated life cycle and climate model of the barramundi was developed based on results from physiological, growth and tagging studies of the species reviewed in Chapter 2. In summary, spawning success is affected by water temperature (Davis 1985; Garrett, Mackinnon *et al.* 1987; Griffin 1987), freshwater flow and hence salinity (Davis 1981; Dunstan 1959; Moore 1982; Sawynok 1998), day length (Griffin 1987) and the tides (Bardach and Santerre 1981; Fishbase 2005; Garrett, Mackinnon *et al.* 1987; MacKinnon 1986). Development from post-larvae through to fingerlings occurs in nursery habitats where salinity and water temperatures affect survival (Fishbase

2005; Russell and Garrett 1985). Most juveniles migrate into coastal creeks and rivers where habitats are affected by water temperature, rainfall and freshwater flow (Davis 1985; Griffin 1985; Griffin 1986; Russell and Garrett 1983). Growth of maturing barramundi is highest in the wet season when both freshwater flow and water temperatures are highest (Davis and Kirkwood 1984; Sawynok 1998). Catchability of fish is influenced by wet season flows that flush mature males into the commercial fishing areas (Platten 1999; Robins, Halliday *et al.* 2005). The life cycle model developed (Figure 3.2) forms the basis of the hypotheses linking climate and commercial barramundi catch.

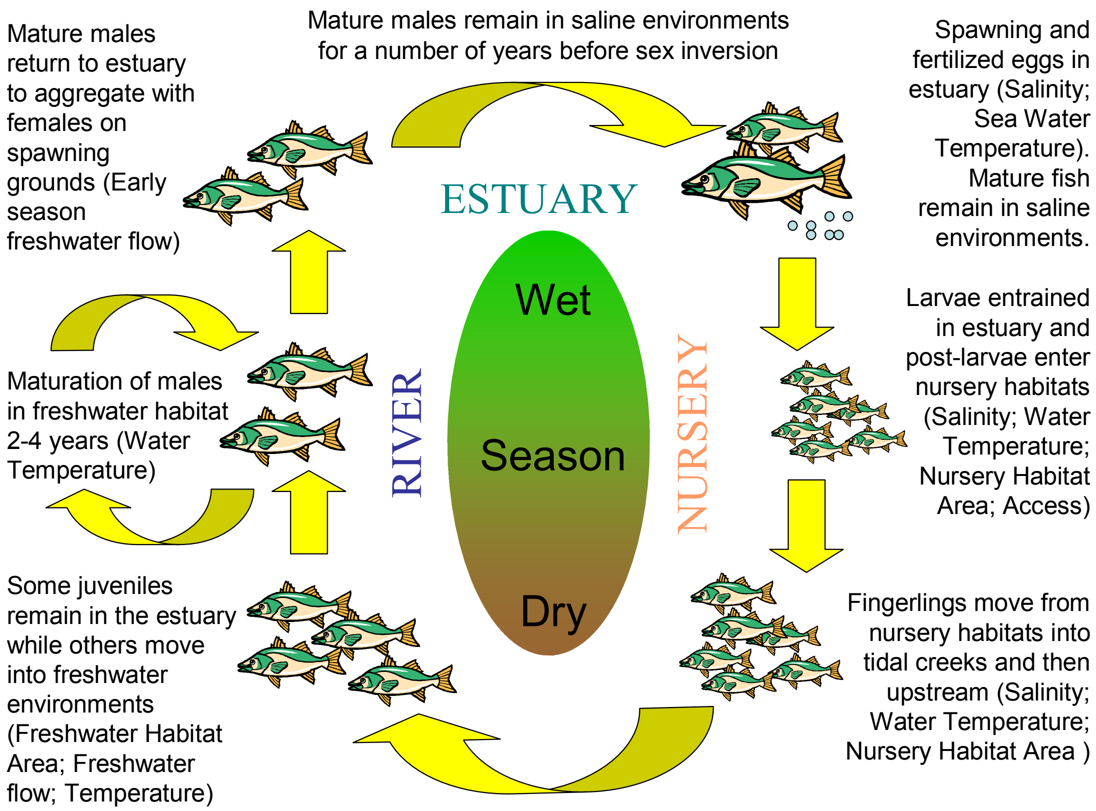


Figure 3.2 Life cycle model of the barramundi including known influences from climate at each stage in the development of the fish (Balston and Williams 2005).

Obviously, climate may impact on individual survival and hence year-class size at a number of stages in the life cycle of the fish and subsequent commercial catch. Figure 3.3 demonstrates this concept for two climate variables: sea surface temperature (SST) and evaporation (E) – variables that are each expected to affect the critical early life stages of the barramundi. The relative size of the fishery (total biomass) at each life cycle stage is indicated by the size of the fish symbol and varies depending on the expected impact from each climate variable. The relative commercial catch a number of years later is indicated by the size of the fish symbols on the bottom line.

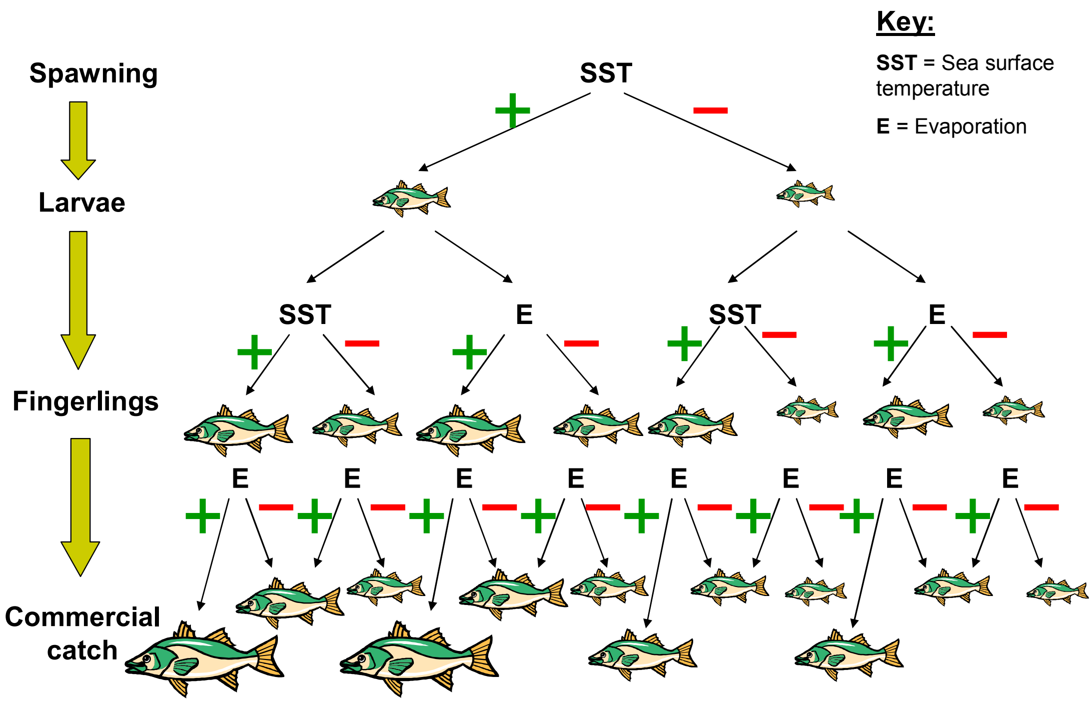


Figure 3.3 Conceptual model of the impact of sea surface temperatures (SST) and evaporation (E) on early barramundi life cycle stages. Variables are either higher than average (+) or lower (-). Relative year-class size at each stage is represented by a fish symbol. The resulting commercial catch is shown along the bottom line. For example, warm SSTs at the time of spawning, followed by low evaporation at the larval and fingerling stage will result in a relatively high catch, as opposed to a sequence of years that starts with low SSTs at the time of spawning and high evaporation at the fingerling stage.

Development of a hypothesis

This concept of compounding impacts from climate at each life cycle stage was used to develop a general hypothesis linking climate and barramundi catch. Each climate variable likely to impact significantly on the species is listed on the left of the table, and the probable effect on each life cycle stage specified in the matrix (Table 3.1). Climate variables that are expected to enhance reproductive success and population growth and result in a high catch a number of years later are marked positive "+", while those labelled negative "-" are expected to hinder reproductive success and population growth and result in a low catch.

Table 3.1 General hypothesis linking climate variability and commercial barramundi catch for north-east Queensland. Each stage in the life cycle of the fish is affected differently by climate. Those conditions that are expected to correlate with increased population and, therefore, catch are indicated by a "+" sign while those that are expected to decrease population size and resulting catch are indicated by a "–" sign. Climate variables that are not linked in the life cycle model to the developmental stage of the fish are marked as not applicable (n/a). Impacts vary depending on the climate variable considered.

Life cycle stage / Climate Variable	Spawning	Larvae	Fingerlings	Juveniles	Maturing males	Returning males
Variable 1	n/a	n/a	+	+	-	-
Variable 2	-	+	+	+	+	+
Variable 3	n/a	+	+	+	+	n/a

For each analysis undertaken (long-term, short-term and threshold), a specific hypothesis table is presented along with the rationale for determining how each climate variable is expected to affect the fishery for each life cycle stage.

Selection of suitable study area and barramundi fishery

To determine firstly the effects from climate on the barramundi fishery, and then the likely effects due to anthropogenic influences (and hence the validity of transferring results from one region to another), both a pristine and an anthropogenically affected area was selected (Figure 3.4). Requirements considered in the choice of suitable study sites were:

1. Barramundi in each study area should, if possible, represent a discrete genetic strain to ensure homogeneity of life cycle stages (i.e. a consistent age to maturity for all individuals in the population);
2. Data for barramundi catch and preferably effort must be available;
3. For the pristine site, impacts from variables other than climate should be minimal in order to obtain the clearest climate signal in catch (i.e. habitat degradation, impediments to freshwater flow, stocking of fingerlings and urban and agricultural development should be negligible).

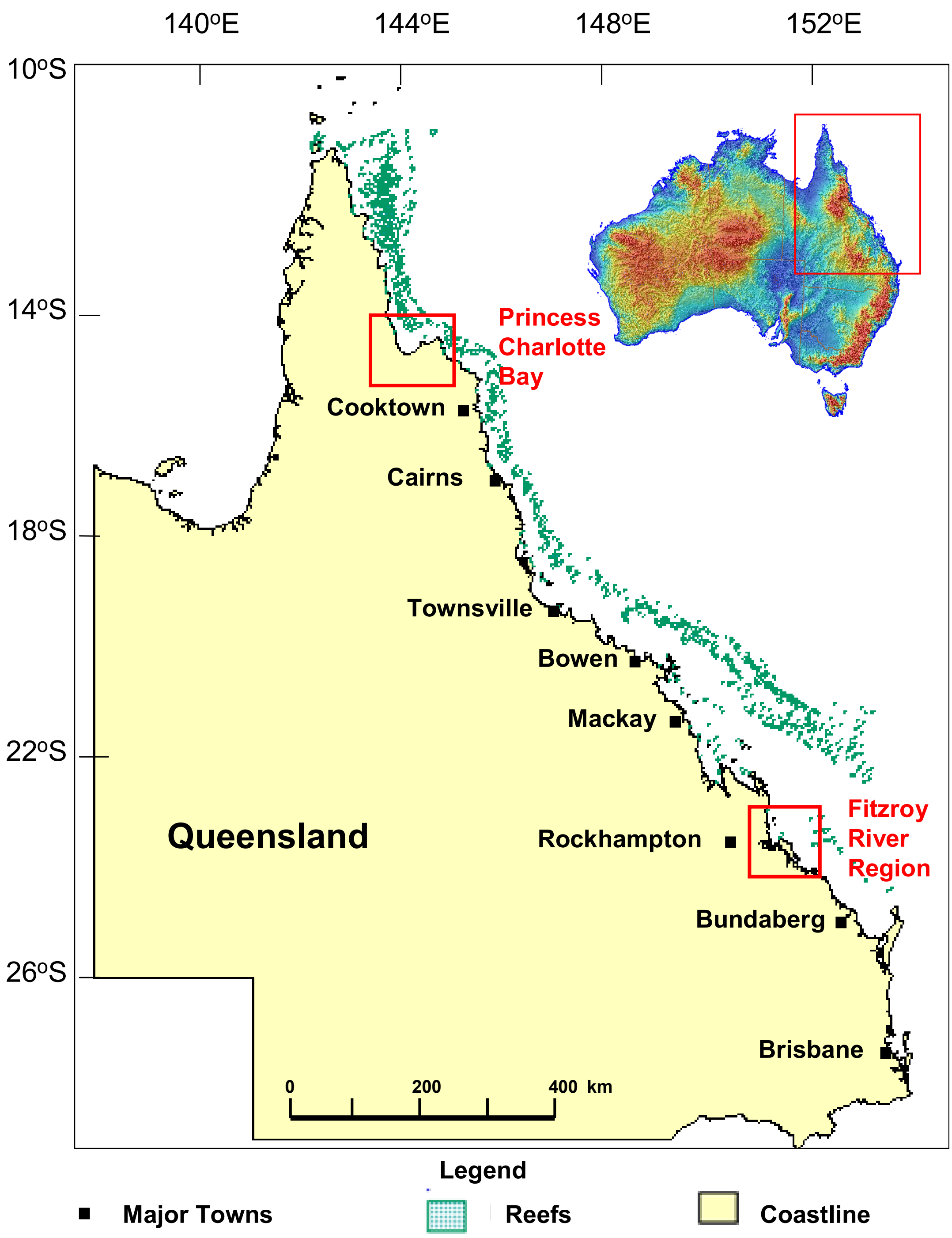


Figure 3.4 Map of Queensland, Australia showing major towns, the Great Barrier Reef and the two areas selected for focused studies of climate impacts on commercial barramundi catch: Princess Charlotte Bay north-west of Cooktown and the Fitzroy River area near Rockhampton.

The near-pristine Princess Charlotte Bay north-west of Cooktown met each of the three requirements and so was selected as the key area for the study. When selecting a study area for a comparative analysis, the Fitzroy River region near Rockhampton meets each of the first two criteria yet has a highly modified catchment.

Collation of fisheries catch and climate data

To determine the spatial and temporal availability of barramundi fisheries catch and effort data, an examination of all possible sources was undertaken (Figure 3.5). The most reliable record of barramundi catch comes from the mandatory recording of commercial catch in a standardised logbook (CFISH) introduced in 1988 by the Queensland Department of Primary Industries and Fisheries as part of the licence retention criteria for the east coast barramundi net fishery (Russell 1988). CFISH logbook data records the location, fishing effort and details of all fish caught in relation to a state-wide grid. Records are only reliable from the 1989/90 financial year onwards, due to teething problems in the first year, and so provide only a relatively short time series of data and so were used for the analyses of short-term climate effects.

The only consistent account of barramundi catch prior to the introduction of CFISH recording was kept by the Queensland Fish Boards. From 1936 – 1945 total weight of fish landed each month for a region extending from Point Danger on the Queensland New South Wales border north to Noosa Heads in south-east Queensland was kept by the Brisbane market. As refrigerated transport was not available at this time, transporting fish large distances would not have been possible and so it is unlikely that these records would include fish landed in northern Queensland. From 1945 – 1980, Fish Boards were operated out of a number of towns along the east coast as far north as Port Douglas (north of Cairns). However, as records were not always a regionally specific account of barramundi landings, total catch from all depots from Gladstone north to Cairns (1946/47 to 1980/81) was used in the analyses of long-term climate effects. Additionally, as there is no record of catch as far north as Princess Charlotte Bay, no measure of effort, and records ceased nearly ten years before the implementation of the mandatory CFISH logbook system, the analysis of long-term and short-term climate impacts had to be undertaken separately. Details of the data, including limitations, are examined more closely in Chapters 4, 5 and 7.

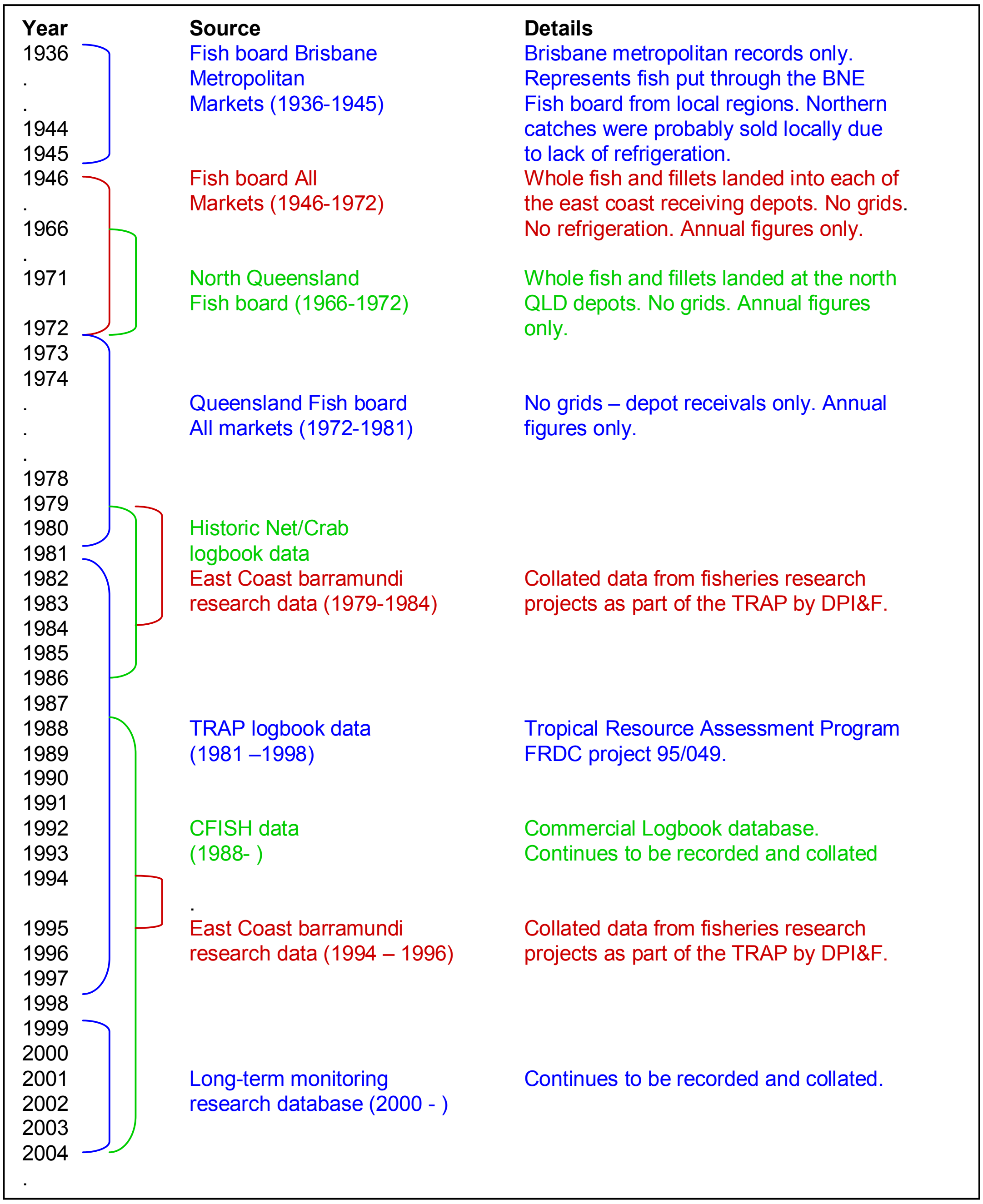


Figure 3.5 Sources of catch and effort data for the Queensland east coast barramundi fishery.

An estimate in the Northern Territory over the 1978/79 season indicated that recreational catch represented approximately 23% of the total catch for the state (Griffin 1982) and so an attempt to quantify recreational catch for Queensland was made. The Queensland Recreational Fishing Data project (RFISH) records recreational fishing activity in Queensland. Surveys undertaken in 1997 concluded that nearly 300,000 barramundi were caught across the state, of which 60,000 (~144 tonnes) were kept, and in 1999 nearly 400,000 fish are estimated to have been caught, of which nearly 120,000 were kept (~288 tonnes) (Higgs 2001). However, as the RFISH data are collected voluntarily by recreational fishers, who use different techniques for capturing the fish at different times of the year on irregular club fishing trips, there are a lot of spatial and temporal inconsistencies in the data (Julie Robins, QDPI&F Fisheries Biologist, pers. comm. June 2004) and so it was not used for statistical analysis. A single study of recreational barramundi fishing in Lakefield National Park (Princess Charlotte Bay) estimated a catch of between 4.4 and 9.4 tonnes of barramundi per annum (Russell and Hales 1993). However, the survey was voluntary and only conducted over a few years (1987 – 1990) and so again was not suitable for use in a statistical analysis.

Of the remaining data sets considered (research studies, Tropical Resource Assessment Program (TRAP) (Magro, Gribble *et al.* 1998) and the Long Term Monitoring Program (Lunow, Garrett *et al.* 2005)), there were other limitations including short data series, missing data or altered assessment techniques. As a result, none of these data were used for statistical analysis but it was considered in the development of the conceptual model, methodology and interpretation of results. In summary, fisheries data sets selected for statistical analysis and modelling were: 1) Fish Board data for all markets north of and including Gladstone for the long-term analyses, and 2) CFISH logbook data for grid squares corresponding to each of the two focus study areas (Princess Charlotte Bay area and the Fitzroy River area) for the short-term analyses.

Analyses

The steps taken in the analyses of data followed the process model (Figure 3.1) and are outlined in more detail within each of the analysis chapters:

Chapter 4: Determine through the use of the life cycle model and correlation analysis short-term climate mechanisms that affect barramundi catch in a relatively pristine area;

Chapter 5: Determine the validity of transferring results from one region to another by comparing results obtained in a pristine environment with those from a highly modified area;

Chapter 6: Identify extreme or threshold climate events that may impact on the fishery in a non-linear way;

Chapter 7: Determine through the use of life cycle model and correlation analysis if there is a relationship between long-term climate mechanisms known to affect the north-east Queensland region and barramundi catch;

Chapter 8: Quantify the proportion of variability in catch resulting from climate impacts at each stage in the life cycle of the fish using regression analysis;

Chapter 9: Develop a model to predict future barramundi catch using climate data;

Chapter 10: Determine possible future impacts of anthropogenic climate change on the fishery by running a suite of future climate scenarios through the predictive model.

3.3 SUMMARY

This chapter presents a process model that outlines the steps followed in this study. Firstly a barramundi life cycle model was developed to identify growth stages affected by climate. The model forms the basis of a general hypothesis linking climate and barramundi catch. Next, suitable study areas and barramundi catch and/or effort data were identified. Finally, the methodology of the study and following chapter content are outlined.

CHAPTER 4: SHORT-TERM CLIMATE EFFECTS: PRINCESS CHARLOTTE BAY

4.1 INTRODUCTION

As reviewed in Chapter 2, previous research has shown that some climate variables have an impact on the survival, reproductive success and/or the catch of barramundi across northern Australia. However, research to date has been limited both in the number of climate variables examined, and the number of locations studied. This chapter addresses research questions 2 (Does short-term (inter-annual) climate variability have an impact on barramundi catch?) and question 3 (Is there a lag between the timing of climate impacts and subsequent barramundi catch?). An examination of inter-annual climate parameters and barramundi catch data for Princess Charlotte Bay was undertaken: a near-pristine study area where anthropogenic modification to habitat is minimal and the effects from climate were expected to be strongest. A description of the study area is followed by an explanation of the data and methodology used in the analysis, including the hypotheses developed to link short-term climate and barramundi catch. Effects from a range of climate variables (freshwater flow, rainfall, evaporation, sea surface temperature (SST)) and climate indices (Madden Julian Oscillation (MJO) and the El Niño/Southern Oscillation (ENSO)) are examined. Results are presented and discussed in both the context of the life cycle of the fish, and how they compare with previous studies.

4.2 STUDY AREA

Princess Charlotte Bay (Figure 4 .1) lies 340 km north of Cairns on the east coast of Cape York Peninsula in the 'North-East Cape York Catchment Area' (DPI 1993). The climate is described as tropical (Bucher and Saenger 1991).

Topography

Apart from low coastal hills on the eastern side of the study area, the topography is relatively flat and slopes gently to the north. Original vegetation and ecosystems have remained relatively undisturbed over the past 200 years and are dominated by Eucalyptus *spp*. and Melaleuca *spp*., open forest, woodland and low woodland (DPI 1993). Soils of the area include sandy alluviums mixed with silt and organic matter, redoxic hydrosols, melanic orthic redoxic hydrosols, eutrophic dermosols, tenosols, vertosols and kandosols. These are sandy, weakly structured soils prone to erosion during heavy monsoonal rainfall if cleared (ANCA 1996).

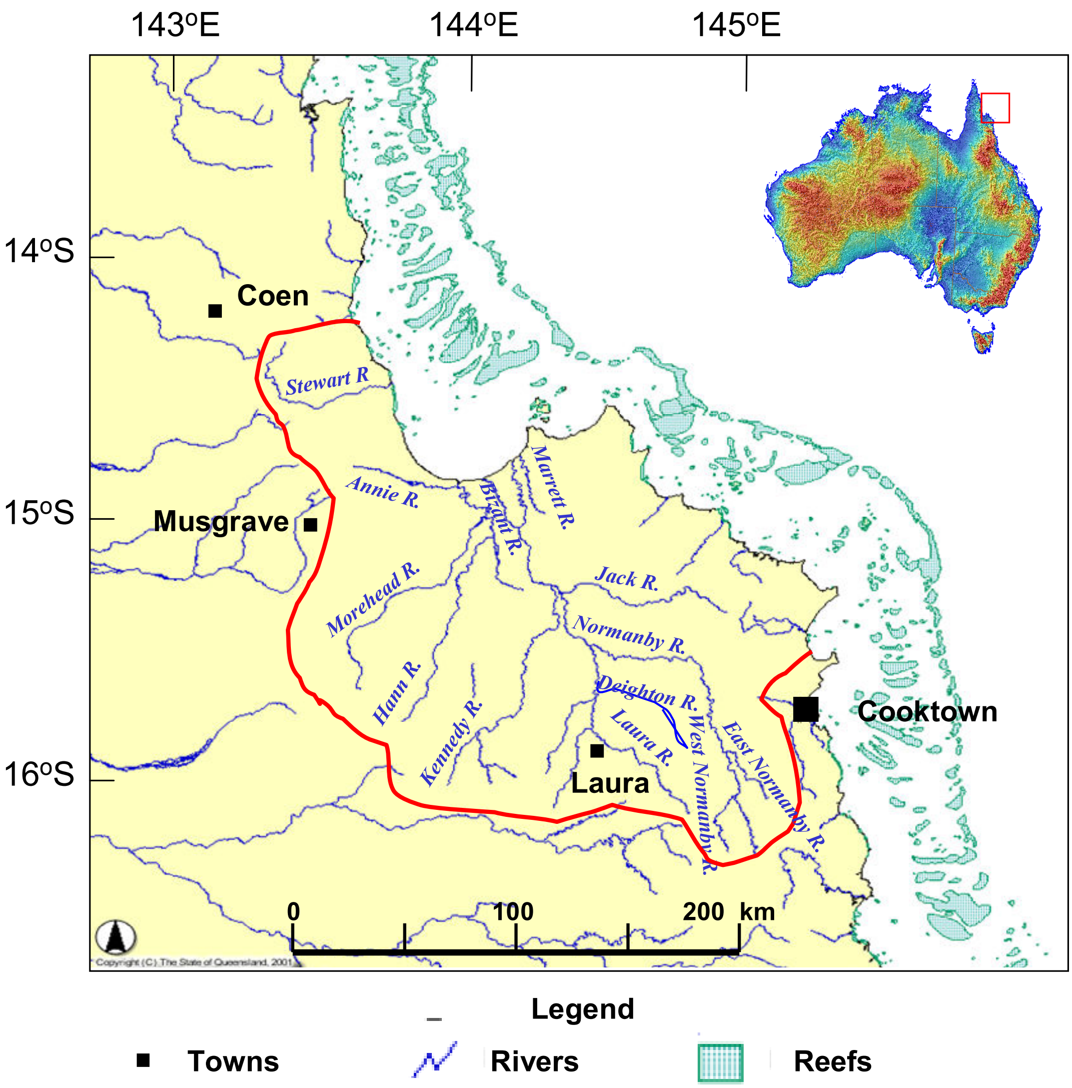


Figure 4.1 The Princess Charlotte Bay study area (Queensland Fisheries Service CHRIS website, November 2006). The study area covers land and inshore areas to the north-east of the red line.

River systems

The rivers that flow into Princess Charlotte Bay are similar to those flowing west to the Gulf of Carpentaria – large meandering rivers with large catchments. Major rivers include the Normanby, Marrett, Laura, Annie, Kennedy, North Kennedy, Morehead and Hann, and there are countless smaller streams which coalesce during the wet season to form extensive wetlands and swamp areas (Russell and Hales 1993). None of the rivers in the basin, including the Normanby which contributes the highest mean annual flow of approximately 1.24 million Ml, have been modified in any major way, and there are only a few small weirs and minimal extraction of water for grazing and national park requirements (DPI 1993).

Land use

The coastal zone and catchment of Princess Charlotte Bay are classified near pristine/relatively undisturbed (Heap, Bryce *et al.* 2001). The majority of the study area (41155 km^2) is used for unimproved, low-density cattle grazing (26 720 km^2), timber reserves and state forest (1 870 km^2), and national park (7 173 km^2). Lakefield National Park is the largest of these covering approximately 5 370 km^2. Agriculture is limited to only 22 km^2 (DPI 1993).

Climate

The climate of north-east Queensland is typical of the tropics and is affected by the Intertropical Convergence Zone (ITCZ) to the north, a band of equatorial trade wind convergence and large-scale convection, and the monsoon and southern monsoon shear line. Sometimes confused with the ITCZ, the monsoon is a large-scale sea breeze circulation created by the continental heating and cooling of the Indian sub-continent to the north, and Australia to the south (Manton and McBride 1992). The monsoon has a pronounced effect on summer (January – March) rainfall and freshwater flow, and contributes up to 80% of the annual rainfall in north Queensland (Lough 2001; Troup 1961). Rainfall for the study area is highly variable (400 – 2000 mm per annum). July and August are the driest months (4 mm each on average) and February the wettest (292 mm average) (Clewett, Clarkson *et al.* 2003). Temperature in the study area ranges from a minimum of about 13^{o}C in July up to a maximum of 35^{o}C in December (BOM 2005).

Estuaries and coastal zone

An estuary is defined in the Queensland Fisheries Act as "the part of a river or inlet up to the limit of tidal influence" (Russell 1988). Estuarine systems include permanent tidal creeks, super- and supra-littoral wetland swamps and display a wide range of aquatic ecosystems. Brackish and freshwater swamps act as nursery habitats for juvenile barramundi by providing abundant prey and protection from predators (Johnston 2005). Fingerlings migrate further into the estuary, coastal streams and/or rivers. Most estuaries in the study area exhibit seasonal variation as a result of tidal influxes, monsoon rainfall in the summer months and dry conditions over the winter (Russell and Garrett 1985).

Catchments emptying into Princess Charlotte Bay and fishing areas to the east to Cape Flattery exhibit a semi diurnal tidal period and low tidal range of 1.90 – 2.10 m (Bucher and Saenger 1991). The estuary is dominated by extensive saline flats and mean wave height varies from 0.15 – 1.1 m and maximum wave height from 1.0 – 2.8 m (Bucher and Saenger 1994; Heap, Bryce *et al.* 2001). Salinities were reported to range from freshwater through to 44 000 $mg.l^{-1}$ salt, and water temperatures from a minimum of $23^{o}C$ to a maximum of $36^{o}C$ (Russell and Garrett 1985). Plant communities include mangroves in the more saline areas, melaluca forests and sedges in the freshwater habitats and mudflats, and eel grass in other areas (Russell and Garrett 1985). The Marina Plains (Lakefield aggregation of wetlands at the head of the Bay) covers an area of 3 920 km^2 and consists of gently undulating alluvial plains, shallow lagoons and old stream channels now in-filled (ANCA 1996). Many of the rivers and smaller tributaries are reduced to a series of waterholes during the winter dry season (Russell and Garrett 1985; Russell and Hales 1993).

Barramundi habitat

The study area is characterized by extensive paperbark woodlands (*Melaleuca viridiflora*), and closed tussock grasslands (*Themeda arguens*) with much of it inundated during the wet season (ANCA 1996). Extensive freshwater swamps are vegetated by Melaleuca forest and sedge (*Elocsharis spp.*) and are usually shallow (<1 m), and dry out in the autumn and winter (Garrett and Russell 1982).

4.3 DATA

Fisheries catch data were extracted from the mandatory CFISH program database and includes both catch (weight) and effort for defined grids along the coast. These data enabled the analysis of a discrete barramundi population caught in a defined area adjacent to a significant, undisturbed wetland habitat. Climate data including freshwater flows, rainfall, sea surface temperatures, terrestrial air temperature, evaporation and indices of the MJO and SOI, were selected from a number of sources. Issues of data quality and/or limitation where they exist are highlighted for each variable, and the collation and preparation of data prior to analysis is described below.

Commercial fisheries logbook (CFISH) data

Within Princess Charlotte Bay, commercial barramundi fishing is undertaken using set nets and is currently limited to tidal waters in the Bay. Apart from seven commercial fisher permits for the Bizant and Normanby Rivers, the remaining rivers and coastal foreshores in the study area are open to all commercial fishermen endorsed to operate in the east coast barramundi fishery (Russell and Hales 1993). Monthly catch and effort data recorded as part of the mandatory CFISH program was extracted for logbook grid squares for the years 1989 – 2002 from the northern edge of Princess Charlotte Bay to Cape Flattery (D10, D11, D12, E11, E12, F11, F12, G12) from the Queensland Department of Primary Industries and Fisheries CFISH program (Figure 4.2). To include all of the individuals spawned in a single year, total catch for each financial year (1 July – 30 June) was calculated. Data for grid squares inland from the coast represent fish caught in rivers and were included in the analysis.

Fishing effort was recorded as the number of boat (net) days (the number of days the nets were set and for which fish were caught). Catch was recorded by individual boats on a daily basis in kilograms. There was no measure of unsuccessful days when no catch was recorded or the number of hours in any one day that the fishers had their nets set (Magro, Bibby *et al.* 1996).

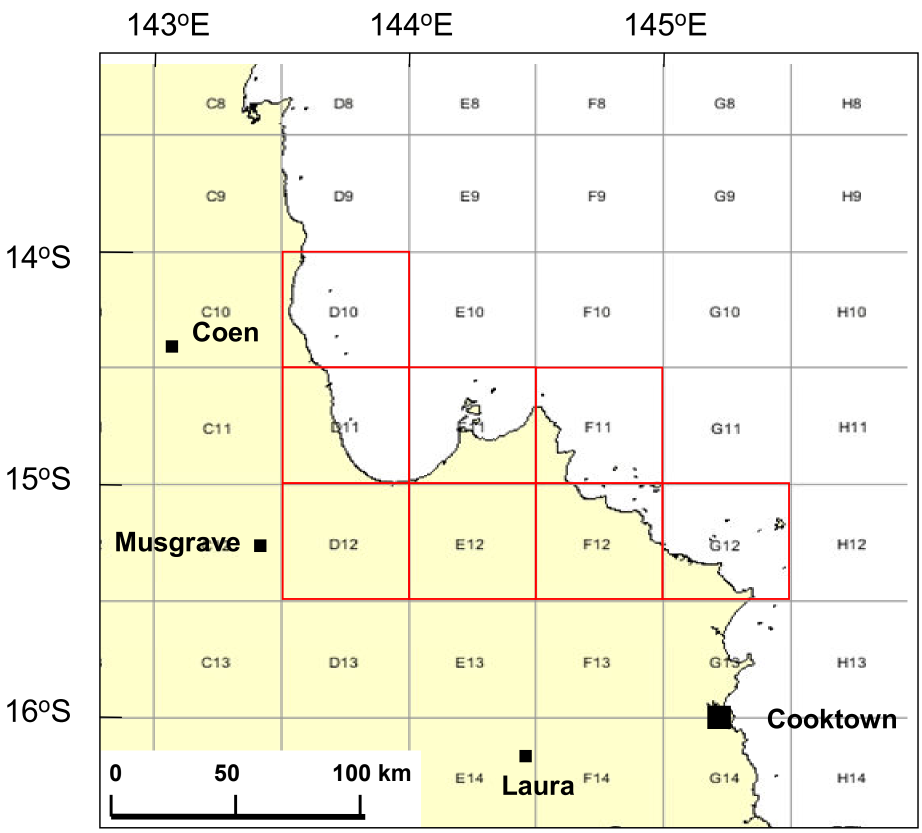


Figure 4.2 CFISH grid squares for the Princess Charlotte Bay study area (Queensland Fisheries Service, March 2006). Grids highlighted in red were included in the analyses.

Metadata for the CFISH data provided by the CHRIS website states that the positional accuracy of the grids was high and that all attributes in the data set were accurate and complete for the years given (CHRIS 2002). This of course relies on the accurate and honest completion of the log sheets by fishers. Anecdotal evidence suggests that in the year the CFISH system was introduced (1988) there was some confusion and under-reporting and so the data sets used in the analysis are those from 1989/90 – 2001/02 (Robins, Halliday *et al.* 2005). Other irregularities of reporting were assumed to remain constant for the years analysed.

Total annual financial year CFISH catch and effort data for the grid points selected in the Princess Charlotte Bay area were plotted (Figure 4.3). The coefficient of determination of 0.13 between catch and effort was not significant at the $p < 0.05$ level, however, to ensure there was no signal from effort in the catch data, catch adjusted for effort (residuals from the regression of catch and effort) was calculated for each year and used for all analyses.

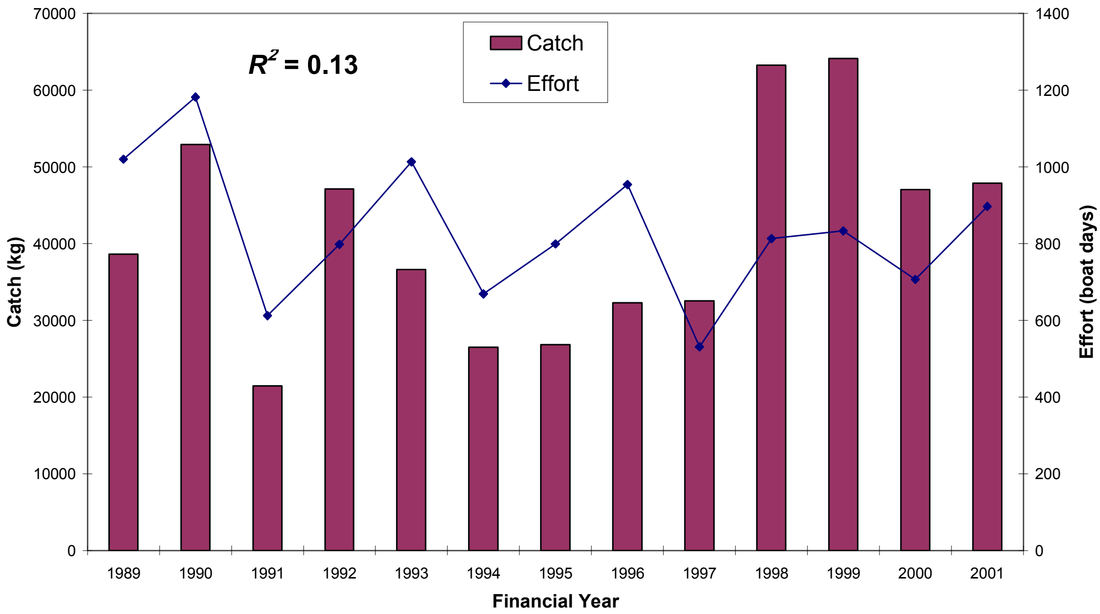


Figure 4.3 Annual financial year (1 July – 30 June) CFISH barramundi catch (bars) and effort (line) for Princess Charlotte Bay (1989/90 – 2001/02).

Climate data

Since the late 19th century, weather data have been collected across Australia by the Bureau of Meteorology (BOM) in accordance with World Meteorological Organisation standards. Data available includes air temperature, rainfall, wind, atmospheric pressure, evaporation, solar radiation and cloud cover. Also recorded by the BOM are details on tropical cyclones including cyclone paths, intensity, wind speed and central pressure. Other data including indices of the SOI and MJO, freshwater flows, SST and tides have been collected by a number of other organisations as outlined in this section. Data were collated for the years of available fish catch data and a lag of up to five years.

Rainfall

As a measure of coastal wetland availability, coastal rainfall data were collated for Princess Charlotte Bay. A scarcity of actual rainfall recordings meant interpolated data had to be used. The BOM SILO database contains interpolated climate surfaces at a daily time-step for a 0.05 degree gridded surface. Methodologies for splining techniques include measures of latitude, longitude, and elevation parameters and are outlined in detail on the SILO website (http://www.bom.gov.au/silo). Interpolated rainfall data for

Princess Charlotte Bay were calculated using the nearest thirty stations that record daily rainfall, and included data from Lakefield National Park recording station (Keith Moodie, Senior Scientific Programmer, QDNRW, pers. comm. November 2005). Average coastal monthly rainfall was calculated using five splined locations that corresponded with the mouth of the Annie (14°30'S 143°42'E) and Normanby Rivers (14°24'S 144°12'E), Port Stewart township (14°06'S 143°42'E), Aloszville Station (14°24'S 144°00'E) and Lakefield National Park headquarters (14°57'S 144°12'E). Long-term historical rainfall for data exploratory analyses were sourced from Australian Rainman for the Musgrave and Laura recording stations (Clewett, Clarkson *et al.* 1994).

Freshwater flow

Monthly freshwater flow data were collected from the Queensland Department of Natural Resources and Water (QDNRW) stream gauge website database (http://www.nrm.qld.gov.au/watershed/index.html) for all gauged rivers flowing into Princess Charlotte Bay – eight in total (Table 4.1). The gauge with the most reliable downstream data was selected for each river.

Table 4.1 Selected stream gauges in the Princess Charlotte Bay (PCB) study area (QDNRW website).

Station Number	Streams in Study Area: PCB to Cape Flattery	Lat.	Long.	Commence date	Cease date
104001A	Stewart River at Telegraph Road	14:10	143:23	18/01/1970	Current
105001B	Hann River at Sandy Ck	15:13	143:50	17/12/1968	Current
105101A	Normanby River at Battle Camp	15:16	144:50	14/12/1967	Current
105102A	Laura River at Coalseam Ck	15:35	144:29	27/03/1968	Current
105103	Kennedy River at Fairlight	15:33	144:01	17/02/1968	06/06/1988
105104A	Deighton River at Deighton	15:29	144:31	29/05/1969	30/07/1988
105105A	East Normanby River at Development Road	15:46	145:00	24/02/1969	Current
105106A	West Normanby River at Mount Sellheim	15:45	144:58	16/12/1970	10/12/1989

The period from January 1971 to February 1987 (a time series of 133 consecutive months) had no missing data (QDNRW Stream gauge website) (Figure 4.4), but due to gauge closures and lengthy gaps in some records after this date, total basin flow data for the period corresponding to the CFISH data (1988 – 2002) was not available. As there is no end-of-system flow model for Princess Charlotte Bay, a statistical model to estimate total basin flow for the years 1988 – 2002 was developed using the good quality base period available (1971 – 1987) and data from those streams for which the high quality data continued through to 2002.

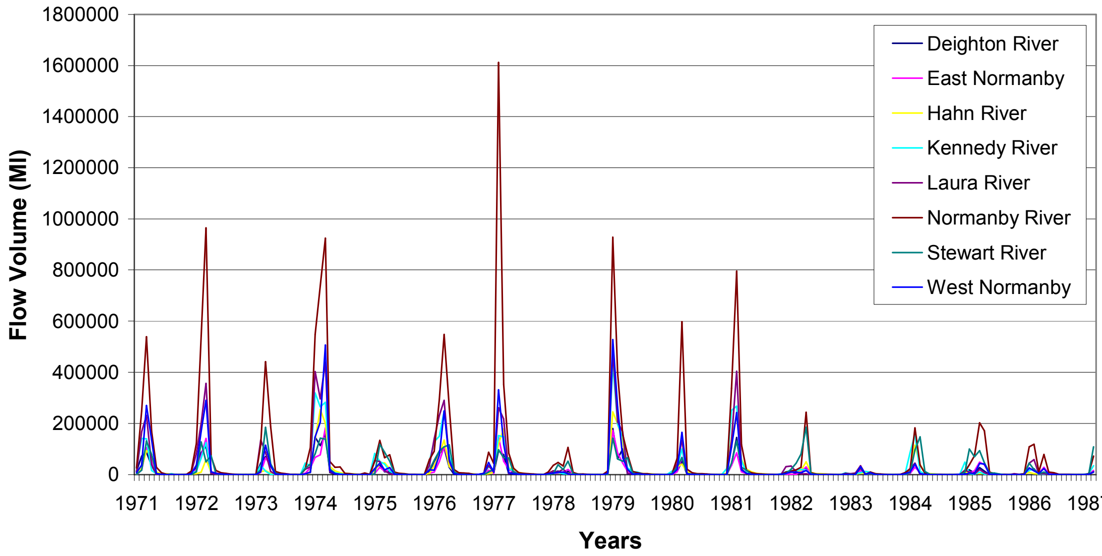


Figure 4.4 Princess Charlotte Bay river flow from January 1971 to February 1987. This data series has no missing values and was used to develop a model to calculate total flow into the basin for the years corresponding to CFISH catch data (1988 – 2002).

To accurately estimate total flow into the Bay using only one or two gauges it was assumed that river flows across the basin were homogeneous. To test the assumption, the frequency distribution of total basin flow over the base period was plotted. The graph was gamma distributed and so non-parametric rank-order gamma correlations between rivers were calculated. Every river was significantly and positively correlated to every other river and to basin flow ($p < 0.05$) for the base period, confirming the assumption (Table 4.2). The Normanby, East Normanby and Laura Rivers each had few missing data beyond the base period and so were selected as input for the total basin flow model. Rivers were prioritised on the basis of their flow volume, data availability and the correlation each river showed with total basin flow.

Table 4.2 Gamma correlations (r) between Princess Charlotte Bay monthly river flows and total basin flow into the Bay (1971 – 1987). All correlations are significant at the $p < 0.05$ level.

River	Gamma correlation
Deighton River	0.86
East Normanby River	0.75
Hahn River	0.72
Kennedy River	0.73
Laura River	0.76
Normanby River	0.87
Stewart River	0.74
West Normanby River	0.87

Using the 1971 – 1987 base period data for each of the selected three rivers, a general linear model with a gamma distributed logarithm link function was calculated (Chandler and Wheater 2002). River flow was log-natural transformed prior to generation of the model. The model included each month as a variable, which allowed it to weight the calculated total predicted basin flow by month (i.e. the model changes for each month) as per Equation 4.1 below.

Monthly Basin Flow =
exp{intercept + *a* **LN*(monthly river flow + 1) (4.1)
+ *b**Jan + *c**Feb + *d**Mar + *e**Apr + *f**May
+ *g**Jun + *h**Jul + *i**Aug + *j**Sep + *k**Oct + *l**Nov}

where: the December coefficient is included in the intercept
exp = exponential
LN = natural logarithm
a,b,c,d, …k,l are the monthly coefficients in Table 4.3.

Example: November 1984, Laura River had a flow of 231.6 Ml

Total Basin Flow = exp{8.3+0.3**LN*(231.6 + 1)+0+0+0+0+0+0+0+0+0+0
- 1.2*1}
= 6922.6 Ml

Table 4.3 Gamma distributed logarithm link function model coefficients for each river used in the calculation of total basin flow into Princess Charlotte Bay as per equation 4.1.

Coefficient	East Normanby	Normanby	Laura
Intercept	7.18082	7.00526	8.31166
Log (Normanby flow) +1 (*a*)	0.43735	0.39615	0.32171
January (*b*)	1.4893	1.23913	0.9403
February (*c*)	1.76844	1.55673	1.52403
March (*d*)	1.65494	1.62053	1.64028
April (*i*)	0.86319	0.86657	1.35675
May (*f*)	-0.32798	-0.19229	0.13507
June (*g*)	-0.83234	-0.71821	-0.25352
July (*h*)	-1.24202	-1.07369	-0.54538
August (*i*)	-1.47374	-1.29096	-0.68111
September (*i*)	-1.70989	-1.22911	-1.07239
October (*k*)	-1.32828	-0.87899	-1.53542
November (*l*)	-0.06624	-0.32935	-1.22222

A Q-Q (or normal probability plot) was used to check that the residuals from each equation were normal (StatSoft. Inc. 2005). Intercept and coefficient values for each river were entered into the model and a time series of total monthly flow into Princess Charlotte Bay was generated using the Normanby River (first priority), East Normanby River (second) and Laura River (third) for the years 1988 – 2002 (refer to Appendix 6 for full data analysis).

Validation of the monthly modelled basin flow against the observed basin flow for the base period gave an $R^2 > 0.9$ for each of the three equations used. However, on the occasions when an extreme river flow event occurred (greater than 1.5 million Ml) the model underestimated total basin flow (Figure 4.5). This limitation of the data was considered further in the analysis of barramundi catch and threshold events (Chapter 6).

<u>Terrestrial air temperature and evaporation</u>

Interpolated maximum and minimum monthly average air temperature and monthly total pan evaporation data were extracted for Lakefield (14°57'S 144°12'E) from the BOM SILO database as a measure of the habitability of shallow nursery wetlands.

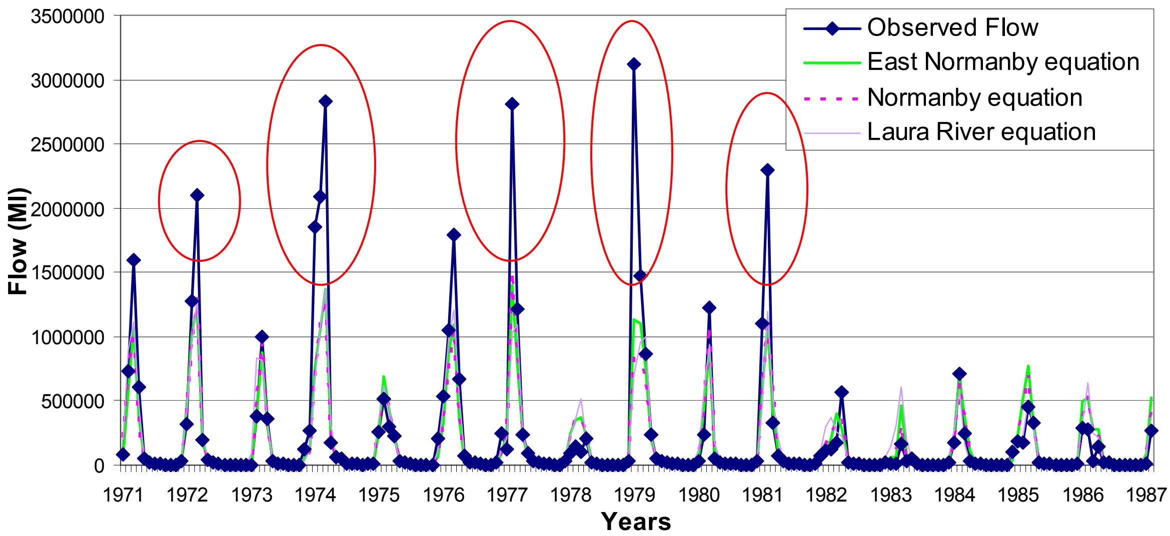


Figure 4.5 Observed versus modelled monthly basin flow for Princess Charlotte Bay (1971 – 1987). Extreme flows over 1.5 million Ml were underestimated by the model (circled in red).

Sea surface temperatures (SSTs)

As there was no in-situ recording of SSTs in Princess Charlotte Bay, data were extracted from the Physical Oceanography Distributed Active Archive Centre (PO.DAAC), provided by the NASA Jet Propulsion Laboratory at the California Institute of Technology (http://podaac.jpl.nasa.gov/products/product119.html). Monthly averaged SST data were extracted for a 1^{o} latitude x longitude box in Princess Charlotte Bay (-14^{o}S 114^{o}E) from the National Centre for Environmental Prediction (NCEP) Reynolds Optimally Interpolated Sea Surface Temperature product. The satellite derived SSTs are from the multi-channel SST products and have an accuracy to within 0.5^{o}C.

Indices of the Southern Oscillation (SOI)

The state of ENSO (as described on page seven) is measured in a number of ways including SSTs, equatorial winds, trade wind anomalies and the Southern Oscillation Index (SOI). The SOI referred to throughout this text, and as used in Australia, is a measure of the difference in air pressure anomalies between Tahiti and Darwin. The index extends back to 1882 and is based on algorithms developed by Troup (1965). Sustained high positive values of the SOI represent a La Niña event and sustained high negative values an El Niño. Monthly average values of the SOI were extracted from the "Long Paddock" website. The index is calculated according to Troup's formulae (Troup

1965) using a base period from 1887 to 1989. (http://www.longpaddock.qld.gov.au/SeasonalClimateOutlook/SouthernOscillationIndex/SOIDataFiles/index.html).

Indices of the Madden Julian Oscillation (MJO)

The 40-50 day wave or Madden-Julian Oscillation (MJO) is considered the strongest intra-seasonal signal in the tropical atmosphere (Anyamba and Weare 1995; Gray 1988; Hendon and Liebmann 1990; Keenan and Brody 1988; Lau and Chan 1986; Madden and Julian 1971; Madden and Julian 1972; Maloney and Kiehl 2001). Early cross-spectral analysis showed the MJO to be a stationary feature on a global scale (though restricted to the tropics), with an eastwardly propagating wave, that included zonal winds that appeared in the Indian Ocean (between 10^{o}N and 10^{o}S) and moved eastwards to the Eastern Pacific as a series of large scale circulation cells every 40 – 50 days (Madden and Julian 1972).

More recent studies indicate that there are other peaks in the spectrum at 17 and 20 – 30 days and that the propagating characteristics of the wave are much more complex than first thought (Anyamba and Weare 1995). The equatorial aspect of the MJO varies in frequency (30 – 53 days) and strength due to changes in ocean temperature in the Pacific region and exhibits higher (lower) frequency with higher (lower) SSTs (Gray 1988; Lau and Chan 1986; Madden and Julian 1971; Maloney and Kiehl 2001). Estimates of how fast the MJO pressure wave 'travels' vary from "some 200 degrees of longitude in 6 to 7 days" (42 – 36 $m.s^{-1}$) (Madden and Julian 1972) down to 1 – 4 $m.s^{-1}$ (Hendon and Liebmann 1990; Madden and Julian 1994) depending on location.

Pulses of the MJO are associated with increased convection and modulation of monsoonal westerlies and often result in increased rainfall and 'active bursts' of a few days in the north Australian monsoon followed by a strong stabilising and drying influence after passing (Hendon and Liebmann 1990). The MJO reaches maximum intensity over the Indonesian-New Guinea region in the austral summer (December – February), and weakens towards the International Date Line (Allan 1988; Madden and Julian 1972; McGregor and Nieuwolt 1998). Research suggests that the MJO influences the timing (but not the intensity) of monsoon active periods, the likelihood and timing of extreme rainfall events (Jones, Waliser *et al.* 2004), and rainfall amount across much of northern Australia (Hendon and Liebmann 1990; Holland 1986; McBride 1987; Wheeler and Hendon 2004) and the Austral – Asian region (Donald, Meinke *et al.* 2006).

All Season Real Time Multi-Variate MJO Indices (RMM) were taken from the Bureau of Meteorology Research Centre website (http://www.bom.gov.au/bmrc/clfor/cfstaff/matw/maproom/RMM/index.htm) and include both phase (as defined by a longitudinal position of the centre of the oscillation) and the number of days in each phase. The variable used in the analysis was a summation of the number of days for phases 1, 4 and 6 from November 1 – April 30 (northern wet season). According to the data, each of these phases has a significant effect on rainfall in the Princess Charlotte Bay area (suppressing, enhancing, enhancing respectively) and is calculated for a time of the year when the MJO has the strongest influence on the east coast of Australia. This period also corresponds with the migration, spawning and early juvenile development of the barramundi.

<u>Data collation</u>

To reduce the number of variables for analysis, and so as to align with the climate patterns of north-eastern Queensland, the seasons were defined as per Vance, Haywood *et al.* (1998): Pre-wet (October – December); wet (January – March); early dry (April – June) and dry (July – September). Additionally, to ensure climate variables selected had a causal link with barramundi production, the life cycle model developed in Chapter 3 was consulted (Figure 3.2).

Variables generated for analyses are as follows:

- Total financial year barramundi catch adjusted for effort;
- Seasonal totals for rainfall and freshwater flow;
- Seasonal average values of the SOI (July – September, October – December, January – March and April - June);
- Maximum air temperature in December and minimum temperature in July. Although temperatures in the study area did not exceed the values for which barramundi are known to occur, maximum air temperatures in December (the hottest recorded month) may have an impact on the survival of young fish

resident in shallow nursery habitats. Additionally, it was hypothesised that minimum temperatures in July (the coldest recorded month) may affect the growth and survival of maturing fish in upstream areas as has been recorded in aquaculture research when temperatures drop below 20^{o}C (Barlow and Rimmer 1989);

- Evaporation was totalled for the financial year as a measure of the availability of shallow nursery habitats leading up to and following spawning;
- The number of days between November 1 and April 30 that the MJO was in each of the phases 1, 4, and 6;
- Average seasonal SSTs corresponding to the arrival of males into the estuary and spawning (October – December and January – March).

In summary, data were taken from what is considered to be the most accurate and complete databases available for the study area at the time of writing. In the case of freshwater flows, where there was no reliable data available, missing values were filled using a general linear gamma distribution model with a gamma distributed logarithm link function, which weighted each month separately. Data for other variables were selected for analyses from peer reviewed data sets on the basis of a well researched barramundi life cycle model (Table 4.4).

Table 4.4 Data used in the analyses of short-term climate effects on the barramundi fishery of Princess Charlotte Bay, and transformations undertaken prior to analyses.

Variable	Source	Format	Notes	Transformations
Barramundi catch adjusted for effort	CFISH database	Financial year total catch	Sum of 8 grids	Untransformed
Madden Julian Oscillation (MJO)	BMRC	Count of days in each phase for November – March	Phases 1, 4 and 6	Untransformed
Southern Oscillation Index (SOI)	QDPI&F and QDNRW Long Paddock website	Average seasonal SOI value	Base period 1887-1989	Untransformed
Freshwater flows	QDNRW Stream gauge site	Total season catchment flow	Sum of 8 gauges	Squared root
Rainfall	BOM SILO database	Total seasonal rainfall	Average of 5 stations	Log Natural +1
Maximum December air temperature	BOM SILO database	Average monthly maximum	Representative grid	Squared
Minimum July air temperature	BOM SILO database	Average monthly minimum	Representative grid	Squared
Evaporation	BOM SILO database	Total annual evaporation	Representative grid	Squared
Sea surface temperatures (SST)	NCEP	Seasonal average	Representative grid	Cubed

CFISH = Queensland Commercial Fisheries Database System; BOM = Bureau of Meteorology; BMRC = Bureau of Meteorology Research Centre; QDNRW = Queensland Department of Natural Resources and Water; QDPI&F = Queensland Department of Primary Industries and Fisheries; NCEP = National Centre for Environmental Prediction (United States).

4.4 METHODS

Methods for the analyses focus on short-term climate effects and follow the steps outlined in Figure 3.1. They are described in more detail below:

1. A hypothesis was designed linking short-term climate variability and barramundi catch for north-east Queensland;
2. An exploratory analysis of the climate variables and CFISH barramundi catch data was undertaken in order to contextualise the timing of the study against long-term climate data and to examine possible relationships;
3. Variables were transformed to ensure normality prior to analysis;
4. A Pearson correlation matrix of selected climate variables was generated in order to identify cases of collinearity (a significant correlation between independent variables);
5. A lag analysis to determine the amount of variability in barramundi catch explained by climate was undertaken by correlating Princess Charlotte Bay barramundi CFISH catch data adjusted for effort (CAE) against each climate parameter for lags of up to five years.

Variables that were not normally distributed prior to statistical analysis were transformed and checked for normality using histograms and the Shapiro Wilk test (Shapiro, Wilk *et al.* 1968). Often in the case of fisheries and climate analysis there are issues of collinearity (e.g. freshwater flow and rainfall) and/or autocorrelation within a variable (e.g. September rainfall correlated with October rainfall). Removing autocorrelation through processes such as prewhitening (removal of red noise from a times series) can increase the risk of a Type II error, or bias results if the source of autocorrelation is due to covariance (Pyper and Peterman 1998). Analyses were therefore undertaken without adjusting either the fisheries or climate data for autocorrelation (e.g. Robins, Halliday *et al.* 2005).

Hypotheses

As introduced in Chapter 3, the likely impact from each climate variable on the life stages of the fish was included into a hypothesis (Table 4.5). Those climate parameters labelled "+" are expected to enhance reproductive success and year-class size in the species and lead to an increase in catch a number of years later, while those labelled "–" are expected to hinder reproductive success and cohort size.

High rainfall over the spawning and early life cycle stages (wet season and early dry season) was expected to increase both the extent of wetland habitat available for fingerlings and juveniles, and upstream habitats for maturing males – and lead to an increase in year-class size and subsequent catch. Increased freshwater flows provide connectivity to the estuary and so were hypothesised to increase the number of fish available for catch in the commercial fishery. Additionally, freshwater flows contribute to wetland nursery habitat area and so an increase in flow was predicted to increase subsequent catch by improving survival of early life cycle stages.

Warm water temperatures are expected to improve the survival of young fish although beyond a certain threshold very high water temperature in shallow wetlands may be detrimental. Warm water temperatures were also expected to increase growth rates of males in freshwater environments. Cold winter water temperatures below a certain threshold have been shown to reduce the survival of even adult barramundi and so the relationship between catch and minimum temperature was hypothesised to be positive. Warm SSTs are associated with increased egg and larvae survival and so a positive relationship between SSTs and subsequent catch was predicted.

Evaporation was hypothesised to have an inverse relationship with catch. Shallow wetland habitats that maintain a nursery environment for fingerlings and juveniles would dry up in years of high evaporation, and reduce the available "carrying capacity" and increase the likelihood of predation from older barramundi and other species including birds. Additionally, very high levels of salinity as a result of high evaporation may be detrimental to the fish at early life stages.

As MJO phase 1 is associated with a significant suppression of rainfall for the Princess Charlotte Bay area during the pre-wet and wet season (Wheeler and Hendon 2004), it was predicted that the variable would be negatively correlated with CAE. On the other hand, Phase 4 and 6 of the MJO are both associated with significant enhancement of rainfall over the same period (Wheeler and Hendon 2004) and so these variables were expected to be positively correlated with CAE.

Positive values of the SOI are generally associated with a La Niña pattern in the central and eastern equatorial Pacific and above average rainfall for the north-east Queensland region. Negative values of the SOI are associated with El Niño conditions and below average rainfall across north-east Queensland. Hence, it was predicted that there would be positive correlations between CAE and the SOI for each season.

Table 4.5 Hypothesis linking climate variability and commercial barramundi catch for north-east Queensland. Each stage in the life cycle of the fish is affected differently by climate. Conditions that are expected to correlate with an increased year-class size and/or subsequent catch are indicated by a "+" sign while those that are expected to decrease year-class size and/or resulting catch are indicated by a "–" sign. Climate parameters that are not linked in the life cycle model to the developmental stage of the fish are marked as not applicable (n/a).

Life cycle stage / Climate variable	Spawning	Larvae	Fingerlings	Juveniles	Maturing males	Returning males
Minimum air temperature	n/a	+	+	+	+	n/a
Maximum air temperature	n/a	+	+	+	+	n/a
Rainfall	n/a	n/a	+	+	+	+
Freshwater flow	-	+	+	+	+	+
Evaporation	n/a	-	-	n/a	n/a	n/a
Sea surface temperature	+	+	n/a	n/a	n/a	n/a
MJO Phase 1	n/a	-	-	-	-	-
MJO Phase 4	n/a	+	+	+	+	+
MJO Phase 6	n/a	+	+	+	+	+
Average Jul-Sept SOI	n/a	+	+	+	+	+
Average Oct-Dec SOI	n/a	+	+	+	+	+
Average Jan-Mar SOI	n/a	+	+	+	+	+
Average Apr-Jun SOI	n/a	+	+	+	+	+

4.5 RESULTS

Exploratory analysis

Annual rainfall data as recorded at the two recording stations in the Princess Charlotte Bay basin (Musgrave and Laura) were extracted from Australian Rainman. The years of available CFISH data are shaded to give an indication of the range of climate variability covered during the study period. The solid line shows the long-term trend in rainfall (Figure 4.6).

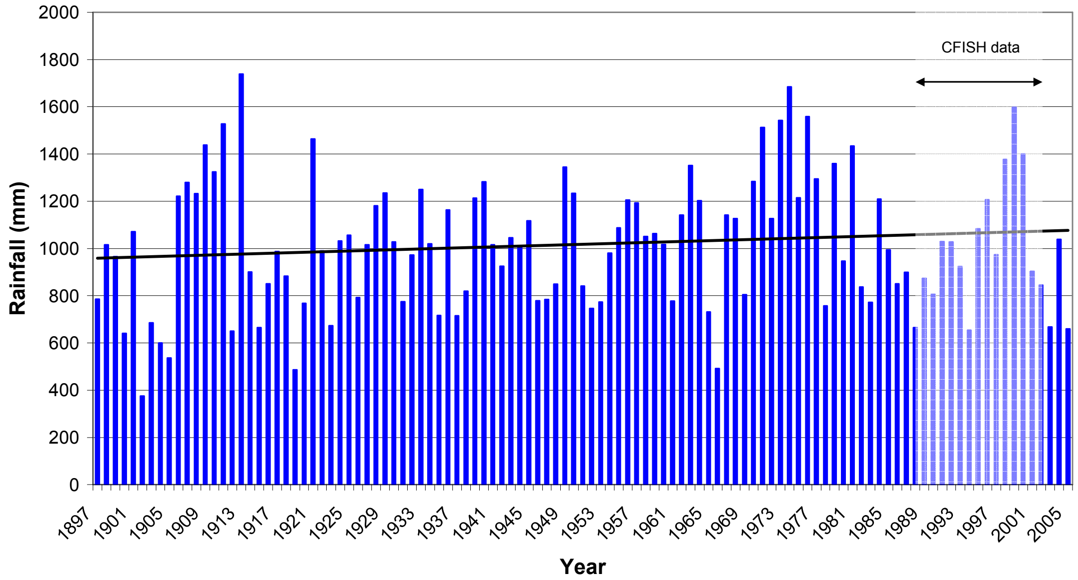


Figure 4.6 Annual average Musgrave and Laura recording station rainfall. The plot indicates annual variability, the long-term trend in rainfall (straight line) and the period of corresponding CFISH data (shaded).

Rainfall in the Princess Charlotte Bay area shows an increasing trend over the past 100 years. The period for which there is CFISH data spans approximately 80% of the variability in rainfall for the region, with at least one year in the highest decile (wettest 10% of years) and one in second lowest decile (driest 20% of years).

Correlation matrix

A correlation matrix of climate indices was generated to check for collinearity (Table 4.6) and shows those variables that are significantly correlated with each other.

Table 4.6 Pearson coefficients of correlation (r) of climate parameters used in the Princess Charlotte Bay analyses. Correlations ≥ 0.57 or ≤ -0.57 are significant at the $p < 0.05$ level and correlations ≥ 0.48 or ≤ -0.48 are significant at the $p < 0.10$ level (n=13).

	Min air temp Jul	Max air temp Dec	Rainfall Jul-Sept	Rainfall Oct-Dec	Rainfall Jan-Mar	Rainfall Apr-Jun	Flow Jul-Sep	Flow Oct-Dec	Flow Jan-Mar	Flow Apr-Jun	Evap Annual	MJO Phase 1	MJO Phase 4	MJO Phase 6	Av Jul-Sept SOI	Av Oct-Dec SOI	Av Jan-Mar SOI	Av Apr-Jun SOI	Av Oct-Dec SST	Av Jan-Mar SST
Min air temp Jul	1.00																			
Max air temp Dec	0.21	1.00																		
Rain Jul-Sept	-0.01	0.19	1.00																	
Rain Oct-Dec	-0.47	-0.79	0.02	1.00																
Rain Jan-Mar	0.09	-0.20	0.75	0.35	1.00															
Rain Apr-Jun	0.26	-0.25	-0.20	0.11	-0.02	1.00														
Flow Jul-Sep	0.07	-0.28	-0.27	0.16	0.02	0.24	1.00													
Flow Oct-Dec	-0.40	-0.74	-0.04	0.83	0.33	0.25	0.30	1.00												
Flow Jan-Mar	-0.22	-0.37	0.67	0.53	0.85	0.05	0.08	0.52	1.00											
Flow Apr-Jun	0.11	-0.58	-0.16	0.43	-0.10	0.74	0.26	0.43	0.14	1.00										
Evap Annual	0.24	0.57	-0.02	-0.63	-0.43	-0.34	-0.57	-0.64	-0.69	-0.42	1.00									
MJO Phase 1	-0.11	0.37	-0.04	-0.29	-0.43	-0.01	-0.60	-0.19	-0.32	-0.04	0.58	1.00								
MJO Phase 4	-0.18	-0.06	-0.08	-0.09	-0.11	0.06	-0.04	0.25	0.11	0.01	-0.13	0.09	1.00							
MJO Phase 6	0.10	-0.32	0.14	0.17	0.29	0.48	0.14	0.08	0.35	0.45	-0.50	-0.25	-0.29	1.00						
Av Jul-Sept SOI	-0.02	-0.51	0.13	0.59	0.33	0.24	0.16	0.27	0.47	0.54	-0.65	-0.53	-0.22	0.64	1.00					
Av Oct-Dec SOI	-0.14	-0.67	-0.04	0.54	0.28	0.37	0.48	0.47	0.52	0.57	-0.87	-0.66	0.11	0.66	0.82	1.00				
Av Jan-Mar SOI	-0.19	-0.41	0.10	0.31	0.30	0.15	0.15	0.25	0.46	0.24	-0.64	-0.66	0.38	0.44	0.66	0.83	1.00			
Av Apr-Jun SOI	0.16	-0.27	-0.20	0.23	0.03	0.94	0.10	0.25	0.14	0.67	-0.44	-0.04	0.09	0.53	0.41	0.46	0.30	1.00		
Av Oct-Dec SST	-0.52	-0.12	0.19	0.17	0.22	0.31	0.22	0.38	0.33	0.03	-0.28	-0.07	0.27	-0.01	-0.24	0.12	0.14	0.23	1.00	
Av Jan-Mar SST	-0.48	-0.12	0.26	0.16	0.40	-0.27	0.46	0.37	0.44	-0.33	-0.44	-0.47	0.20	0.01	-0.11	0.28	0.34	-0.33	0.61	1.00

Lag analysis

Scatter plots of selected climate parameters and barramundi CAE were generated for lags of up to five years to identify likely relationships (Appendix 3). A number of plots at different time lags showed significant linear relationships between climate and CAE. Other plots showed a non-linear relationship between climate and CAE and these were examined in more detail in Chapter 6 (extreme and threshold climate events). A Pearson correlation matrix of CAE versus each climate variable (Table 4.7) and each climate index (Table 4.8) was generated for lags of up to five years.

Table 4.7 Pearson coefficient of correlation (*r*) between Princess Charlotte Bay barramundi CFISH catch adjusted for effort (1989/90 – 2001/02) and climate variables (zero – five year lag). Highlighted correlations significant at the $p < 0.05$** and $p < 0.10$* levels.

Climate Variable	Zero lag	1 year lag	2 year lag	3 year lag	4 year lag	5 year lag
Minimum air temperature Jul (^{o}C)	0.10	-0.16	-0.25	-0.62**	-0.27	-0.52*
Maximum air temperature Dec (^{o}C)	-0.55*	-0.25	-0.02	0.06	0.21	0.11
Rainfall Jul-Sept (mm)	-0.01	0.02	0.77**	0.46	0.48*	0.28
Rainfall Oct-Dec (mm)	0.56**	0.30	0.38	0.15	-0.06	-0.31
Rainfall Jan-Mar (mm)	0.56**	0.31	0.62**	0.12	0.26	-0.05
Rainfall Apr-Jun (mm)	0.37	0.40	-0.02	0.14	0.08	-0.19
Flow Jul-Sep (Ml)	0.36	0.41	0.33	0.18	-0.34	-0.11
Flow Oct-Dec (Ml)	0.71**	0.37	0.29	-0.02	-0.13	-0.09
Flow Jan-Mar (Ml)	0.52*	0.35	0.76**	0.36	0.43	0.00
Flow Apr-Jun (Ml)	0.33	0.33	0.13	0.27	0.08	-0.26
Evaporation Annual (mm)	-0.73**	-0.48*	-0.62**	-0.34	-0.15	0.38
Average Oct-Dec SST (^{o}C)	0.12	0.25	0.40	0.46	0.56**	0.55*
Average Jan-Mar SST (^{o}C)	0.32	0.17	0.58**	0.03	0.29	0.33

Concurrent correlations (no lag) identified seven significant correlations: maximum temperature December (negative), pre-wet season (October – December) rainfall (positive), wet season (January – March) rainfall (positive), pre-wet season freshwater flow (positive), wet season freshwater flow (positive), annual evaporation (negative) and average pre-wet season SOI (positive). At the one year lag there were only two significant correlations: annual evaporation (negative) and MJO Phase 6 (positive). For a lag of two years, there were a number of significant correlations: dry season (July – September) rainfall (positive), wet season rainfall (positive), wet season freshwater flow (positive), annual evaporation (negative), average wet season SST (positive). Three years prior to catch minimum temperature July was the only variable significantly correlated with CAE (negative). Four years prior to catch there were significant correlations between CAE and dry season rainfall (positive), average pre-wet season SST (positive) and MJO Phase 4 (positive). At the five year lag again average pre-wet season SST (positive) and MJO Phase 4 (positive) were both significant as well as minimum temperature July (negative).

Table 4.8 Pearson coefficient of correlation (*r*) between Princess Charlotte Bay barramundi CFISH catch adjusted for effort (1989/90 – 2001/02) and short-term climate indices (zero – five year lag). Highlighted correlations significant at the $p < 0.05$** and $p < 0.10$* levels.

Climate Index	Zero lag	1 year lag	2 year lag	3 year lag	4 year lag	5 year lag
MJO Phase 1	-0.55	0.00	-0.26	-0.08	0.17	-0.16
MJO Phase 4	0.04	-0.39	-0.18	0.05	0.54*	0.67**
MJO Phase 6	0.38	0.50*	0.16	0.21	-0.09	0.06
Average Jul-Sept SOI	0.47	0.12	0.29	0.13	0.06	-0.47
Average Oct-Dec SOI	0.62**	0.19	0.29	0.14	0.14	-0.20
Average Jan-Mar SOI	0.47	-0.18	0.10	0.19	0.37	0.34
Average Apr-Jun SOI	0.41	0.26	-0.04	0.15	0.09	-0.06

4.6 DISCUSSION

The years of barramundi catch data spans approximately 80% of the climate variability as measured by rainfall at Musgrave and Laura stations over the past 109 years. This result provides some reassurance that despite the short time series of data available for analysis, most of the range in rainfall occurs over the period of the study. Additionally, ENSO oscillated between both El Niño (1991/92, 1994/95, 1997/98 and 2002/03) and La Niña (1988/89, 1996/97, 1998/99, 1999/00 and 2000/01) representing the full cycle of the inter-annual variability in the Pacific Ocean. The long-term trend in rainfall is perhaps indicative of anthropogenic climate change and is discussed further in Chapter 9 (Effects of climate change: Princess Charlotte Bay).

As might be expected, a number of the climate parameters were significantly correlated with at least one other climate variable at the $p < 0.05$ (Table 4.7), a fact that was taken into consideration when interpreting the results. In some cases a physical mechanism to explain the relationship is not obvious (e.g. dry season rainfall correlated with early dry season freshwater flow) and so the significant result may instead be spurious due to the large number of parameters tested.

Significant correlations between climate and barramundi catch adjusted for effort (CAE) in the year of catch have most likely identified an effect of climate on fish catchability. A study in the Fitzroy area attributed 41% of the variability in catch to summer (December – February) freshwater flow and 45% to summer rainfall (Robins, Halliday *et al.* 2005). The results from the present analyses were similar. Pre-wet and wet season rainfall each explained 31% of the variability in annual CAE, and pre-wet season freshwater flow explained 50% of the variability in CAE. Wet season freshwater flow explained 27% of the variability in CAE. The results reinforce the observation that mature males return to the estuarine environment at the beginning of the wet season in response to the increased rainfall and freshwater flows that improve the connectivity between freshwater habitats and the ocean (Dunstan 1959). Although concurrent rainfall and flow parameters were significantly correlated (Table 4.7), flow is likely to have the strongest effect – both because it explains the highest proportion of variability in CAE and is the logical option when the behaviour of the fish and the habitat are considered. The pre-wet season SOI is a measure of ENSO activity and to some degree rainfall and freshwater flow for the region, was also significantly correlated with catch. For the period of the study, the SOI at this time of the year is significantly correlated with rainfall.

Although both annual evaporation and maximum air temperature in December were significantly and negatively correlated with CAE in the year of catch, there is no clear reason why either of these variables would have an influence on the catchability of the fish. In the Northern Territory, Griffin (1986) reported that an increase in the catch of tagged barramundi moving downstream into the estuary occurred as temperatures increased over the dry season (July – September). However, the authors do not propose a causal link between increasing temperature and catch, and the observation goes contrary to the result in this study. It could be instead that the significant and negative correlation between both maximum December temperature and annual evaporation with pre-wet season rainfall and flow explains the result, as wetter seasons would have more cloud cover and so maximum temperatures and evaporation would be reduced.

Interpretation of the correlation results between barramundi CAE and the climate parameters at various lags took into account the life cycle of the species (Chapter 3, Figure 3.2). The identification of a lag between climate influences and catch has been undertaken in earlier studies of barramundi with mixed results (e.g. Griffin 1986; Robins, Halliday *et al.* 2005). It appears that the time between spawning and catch varies with population and location. Early research based on age length models for barramundi indicated that fish are four years old or more before entering the commercial fishery. However, it was recognised that growth rates for the species range considerably between genetic stocks (Shaklee, Salini *et al.* 1993) and even from one river to the next. Male barramundi in river systems north of 15°S on both the east and west coasts of Cape York Peninsula were found to be breeding as young as one or two years old (Davis and Kirkwood 1984; Garrett 1986). More recent work using sagittal otoliths (ear bones) to age the fish have shown fish as young as one and two years of age have been caught in the commercial fishery, although the highest proportion of fish caught in the October – February harvest in the Fitzroy River area were three years old (Staunton-Smith, Robins *et al.* 2004). Unfortunately, the relationship between total length and age is inconsistent as fish caught in the Fitzroy area ranged in age from two to thirty-two years (Staunton-Smith, Robins *et al.* 2004). Age structure data like this does not exist for the barramundi of Princess Charlotte Bay. However, observation suggests fish in the area grow to commercial size in a similar two to four years (Rod Garrett, QPDI&F, Principal Fisheries Biologist, pers. comm. July 2005). Although there would have been some individuals that were older in each years catch, the financial year measure of catch used in this study was selected to include as many fish spawned in the same year as possible (i.e. the same year-class). Finally, selectivity for certain sized fish has remained the same as commercial gear has not changed over the period of the study and so the selection of fish in the population caught should have remained the same.

The analyses returned a number of significant correlations between climate parameters and barramundi CAE two years prior to catch, suggesting that barramundi in Princess Charlotte Bay are growing to commercial size within two to three years, depending on the time of spawning and time of catch. These results agree with previous observations. The significant positive correlation between CAE and wet season SSTs two years prior to catch is, perhaps, the clearest measure of the lag as it represents the time of the year when fish are spawning in the estuary and no other lag between CAE and wet season SST is significant. Additionally, wet season SSTs are not significantly correlated with any other variable considered. Certainly, eggs are particularly sensitive to water temperature (Pauly and Pullin 1988) and spawning is thought to be triggered by the seasonal increase in water temperature (Garrett, Mackinnon *et al.* 1987).

Both rainfall and freshwater flow in the wet season were also significantly correlated with CAE two years prior to catch. This is the time of year when fingerlings and juveniles inhabit the nursery swamps and wetland areas. In other studies, each of these variables have been associated with increased numbers of young-of-year fish in nursery habitats (Davis 1985; Griffin 1985; Griffin 1986; Russell and Garrett 1983). Although these two variables were correlated, it is possible that they each describe a mechanism that affects the fishery in a different biological way. For example, flow in the river bed versus rainfall replenishing wetland habitat separate from the river (e.g. Robins, Halliday *et al.* 2005).

The highest significant correlation between CAE and climate was with dry season rainfall. Rainfall at this time of year is minimal (0 – 21 mm over the period of the study) and so it is interesting that there was such a strong relationship. It could be that rainfall at this time of year maintains wetland habitats that would otherwise dry out and result in high mortalities. Or, it may be that the rainfall wets the soil profile and so prepares the wetland areas for early inundation. Research in the Northern Territory (Griffin 1985) has shown that spawning there occurs in the very early months of the wet season, before the regular monsoon rains, and that the success of this early spawning significantly depends on the amount of rain that falls to replenish water levels in supralittoral swamps. Rainfall over the dry season is not significantly correlated with rainfall over the pre-wet and so there is no measure of autocorrelation in the result.

Annual evaporation, a variable that has not been considered in earlier studies, gives a significant inverse relationship with barramundi CAE both one and two years prior to catch. As mentioned earlier, evaporation is significantly correlated with other variables including rainfall and freshwater flow. However, it could also be that evaporation is an effective measure of the available wetland and nursery habitats in Princess Charlotte Bay, as evaporation was the only variable significantly correlated with CAE in the year prior to catch. Research in the Northern Territory (NT) indicates that the area of available nursery habitat appears to be the strongest measure of population fluctuation in barramundi (Griffin 1985). Most of the wetlands in Princess Charlotte Bay are less than 1 m in depth, which would make them prone to drying out (Garrett and Russell 1982). Annual evaporation over the years of the study averaged 2125 mm while rainfall averaged only 1142 mm. Depending on how and when the rain falls (and input from river flow), it is possible that these wetland areas dry out while larvae and fingerlings are in residence. Further analysis of the relationship between barramundi CAE and evaporation at the seasonal scale indicated that the highest correlation (r = -0.76) was with wet season evaporation two years prior to catch, just when the young-of-the-year are in the nursery habitats. It could be that a measure of water balance for each season (rainfall minus evaporation) would prove an even better estimate of nursery habitat and therefore early life cycle survival – an analysis beyond the scope of this thesis. In years when the wetlands do not dry out completely, a dramatic reduction in habitat area would increase predator pressures both from larger resident barramundi (Davis 1985) and birds (Johnston 2005). Finally, as the nursery habitats dry out, salinity would increase to a level that is perhaps uninhabitable by the young fish. Generally though, barramundi appear to be quite tolerant of high salinity environments and fingerlings have been recorded in water with salinities as high as 94 ppt (Russell and Garrett 1983).

None of the climate index parameters (MJO or SOI) were significantly correlated with barramundi CAE two years prior to catch. The relationship between the concurrent SOI and rainfall over the period of the study is weak and the only significant correlations were between the pre-wet season rainfall and SOI, and the pre-wet season rainfall and the dry season SOI. The relationship between wet season rainfall and the SOI for any season was not significant in this study at Princess Charlotte Bay for the years of available data. A number of studies have found that the relationship between the SOI and rainfall across north-east Australia (and other climate variables including tropical cyclone activity) has varied over time (Lough 1999; Nicholls 1992). Such changes in the strength of the relationship between the two are the result of influences from decadal scale climate cycles such as the IPO (Meinke, deVoil *et al.* 2005; Power, Casey *et al.* 1999) and are examined further in Chapter 7 (Long-term climate effects: north-east Queensland). Phase 6 of the MJO was positively and significantly correlated with barramundi CAE in the year prior to catch. As a measure of rainfall enhancement it is possible that this result confirms that wetter conditions are conducive to barramundi survival in the one to two year age group. However, the correlation between MJO Phase 6 and both rainfall and flow over the pre-wet and wet seasons was not significant. None of the other parameters tested were significantly correlated with barramundi CAE either one or two years prior to catch. In summary, each of the significant correlations between barramundi CAE and climate two years prior to catch describe climatic conditions that would result in an extensive and conducive nursery habitat for young-of-year barramundi survival: high wet season rainfall and freshwater flows, high dry season rainfall, warm wet season SSTs and low annual/wet season evaporation.

Significant correlations between barramundi CAE and climate variables at longer lags (i.e. minimum temperature in July three and five years prior to catch, dry season rainfall four years prior to catch, and average pre-wet season SSTs four and five years prior to catch) are more difficult to interpret as the effect, if there is one, must be assumed to be pre-spawning. Obviously, there is a statistical probability that some of the significant correlations are an artefact of chance and do not represent a valid causal link. The consistently negative correlation between minimum July air temperature and barramundi CAE (significant three and five years prior to catch) is counter-intuitive: the warmer the minimum temperatures the lower the subsequent catch. Both previous research (e.g. Agcopra, Balston *et al.* 2005), and the barramundi life cycle model indicate reduced survival of individuals in colder conditions (below 20^{o}C). Air temperatures in Princess Charlotte Bay often get below 20^{o}C in July, although, mature adults in the estuary at that time are not likely to be strongly affected by minimum air temperatures apart from an inflow of freshwater, which in July would be minimal. It could be instead, that there are higher order mechanisms at work that we do not yet understand (e.g. predator/food-web interactions) (Rod Garrett, Fisheries Biologist, Queensland Department of Primary Industries and Fisheries, pers. comm. July 2006). This possibility may also explain the positive correlation between dry season rainfall and barramundi CAE four years later as again a direct causal link between the two would not be expected unless increased flow at this time of year increases primary production in the estuary. The consistently positive correlations between pre-wet season SSTs and barramundi CAE for all lags (and significantly four and five years before catch) may describe the improved survival of brood stock in the estuary, or again a more complex higher order connection.

Barramundi are highly fecund fish (Davis 1984), capable of producing thousands of eggs per female. Because of this it is likely there is only a limited relationship between adult stock densities and larval recruitment. In other words, a low number of females in the population would be unlikely to limit year-class numbers. Additionally, current management arrangements with respect to legal fish sizes and closed seasons aim to protect spawning adults. As a result, it is probable that environmental or habitat factors and not biological limitations are reducing the young-of-the-year. This assumption is strengthened by recent research in the Fitzroy River area that has shown less than 1% of juvenile fish survive to adulthood (Johnston 2004).

When interpreting these results it is necessary to take into account the limitations of the data used and assumptions made. Evaporation, rainfall and air temperature are all modelled variables calculated from instrument readings taken at local stations in the region. In Princess Charlotte Bay, however, recording stations are sparse and so data for the coordinates corresponding to the study area will incur a degree of spatial error. Catch data, although with a record of effort, is a measure of the number of days the nets are set and fish are caught – not the total number of days/hours of fishing. Additionally, recreational fishers take a significant proportion of the biomass (estimated in the Northern Territory at approximately 23% of total catch (Griffin 1982)). Without good quality recreational catch data for Princess Charlotte Bay this component of catch is assumed to be constant from one year to the next, although, in very wet years access to the area is limited and effort would be low. Finally, as with all fisheries analyses that have only catch and effort data as a measure of biomass, the assumption is made that landed fish represent a consistent proportion of the fishery from one year to the next and that records are accurate.

A summary of the results from the short-term analyses between climate and barramundi CAE were compared with the hypothesis developed (Table 4.9). Apart from the unexpected significant negative correlation between CAE and minimum July temperatures, which has no logical explanation, all other variables had either the predicted effect or were not significant.

Table 4.9 Summary of findings from the correlation analyses between Princess Charlotte Bay barramundi catch and short-term climate parameters compared to the hypothesis presented in Table 4.6. Parameters that were expected to correlate with increased population and therefore catch are indicated by a "+" sign while those that were expected to decrease survival and resulting catch are indicated by a "–" sign. Climate variables that are not linked in the life cycle model to the developmental stage of the fish are marked as not applicable (n/a). Correlations that were significant at the $p < 0.10$ level or less and confirm the original hypothesis are shaded in grey. Correlations that were not significant are left without highlight and those that were significant and opposite in sign to that predicted are hatched ▨ .

Climate variable \ Life cycle stage	Spawning	Larvae	Fingerlings	Juveniles	Maturing males	Returning males
Minimum terrestrial air temperature	n/a	+	+	+	+	n/a
Maximum terrestrial air temperature	n/a	+	+	+	+	n/a
Rainfall	n/a	n/a	+	+	+	+
Freshwater flow	-	+	+	+	+	+
Evaporation	n/a	-	-	-	n/a	n/a
Sea water temperature	+	+	n/a	n/a	n/a	n/a
MJO Phase 1	n/a	-	-	-	-	-
MJO Phase 4	n/a	+	+	+	+	+
MJO Phase 6	n/a	+	+	+	+	+
Average Jul-Sept SOI	n/a	+	+	+	+	+
Average Oct-Dec SOI	n/a	+	+	+	+	+
Average Jan-Mar SOI	n/a	+	+	+	+	+
Average Apr-Jun SOI	n/a	+	+	+	+	+

4.7 CONCLUSION

The near-pristine, tropical ecosystems of Princess Charlotte Bay in north-east Queensland provided an ideal location for an analysis of climate impacts on the barramundi fishery as there were very few of the anthropogenic impacts seen in other areas along the coast. The years of the study represented at least 80% of the centennial variation in climate as measured by rainfall at Musgrave and Laura stations. The long-term trend for rainfall in the area is slightly increasing and may be an indication of anthropogenic climate change (see Chapter 9 for more detail).

Short-term relationships between the climate variables and barramundi catch and effort data (CAE) for the period 1989/90 – 2001/02 were examined for lags of up to five years. Two years prior to catch a number of significant correlations between barramundi CAE and climate variables indicate that barramundi in the area are spawning and young-of-year inhabiting the nursery habitats at this time. High wet season rainfall and freshwater flows, high dry season rainfall, warm wet season SSTs and low annual/wet season evaporation were all significant two years prior to catch. Each of these variables describes climatic conditions that would result in extensive and conducive nursery habitats for young-of-year barramundi and a likely increase in survival.

Significant correlations in the year of catch confirm the observation that mature males are flushed into the estuarine environment at the beginning of the wet season as increased rainfall and freshwater flows improve connectivity between freshwater habitats and the ocean. Both rainfall and freshwater flow in the pre-wet and wet seasons (October – March) were significantly and positively correlated with barramundi CAE.

Climate indices (SOI and MJO) returned only two significant correlations with barramundi CAE up to two years before catch: October – December SOI (as a measure of pre-wet season rainfall) was significant in the year of catch, and MJO Phase 6 (a measure of enhanced rainfall in the area) was positively correlated with barramundi CAE the year before catch.

In summary, results from the short-term analyses indicated that climate is having a significant impact on the catch of barramundi in Princess Charlotte Bay in ways that would be expected when the life cycle of the fish is taken into account. These findings provide the potential for predicting future catch using climate data. How clear these effects are in a highly modified catchment is examined next in Chapter 5 (Comparative analyses: Fitzroy River area).

CHAPTER 5: COMPARATIVE ANALYSIS: FITZROY RIVER AREA

5.1 INTRODUCTION

Chapter 5 applies the processes and methodology used in the analyses of short-term climate and barramundi catch in the pristine, tropical, monsoonal area of Princess Charlotte Bay to the Fitzroy River area, a sub-tropical environment with anthropogenically modified catchments and near-shore areas. The chapter addresses research questions 2 and 3 for the Fitzroy area, and question 4 (Do anthropogenic impacts mask the effect of climate impacts on fisheries catch?). Results are compared to those for the Princess Charlotte Bay area and the validity of transferring methodologies and results between regions is discussed.

5.2 STUDY AREA

Topography

The coastal delta and floodplains of the Fitzroy River area represent the end point of the largest river system in Queensland and consist predominantly of quaternary alluvial and marine deposits of silt, clay, sand and gravel (ANCA 1996). The city of Rockhampton is the major population centre and the climate is described as sub-tropical (Bucher and Saenger 1991) (Figure 5.1).

River systems

The Fitzroy River basin covers 142 645 km^2 and comprises six major sub-catchments drained by the Nogoa, Comet, Mackenzie, Isaac, Dawson and Fitzroy Rivers (DPI 1993). All of these meandering systems provided good barramundi habitat in the lower reaches prior to the construction of the Fitzroy River tidal barrage, about 50 km upstream of the river mouth, in 1970. An upgrade to the barrage fishway in 1994 now allows for the migration of some fish upstream. A flood in 1991 cut out a 10 km loop of the river and changed the hydrology of the Fitzroy River significantly (Robins, Halliday *et al.* 2005).

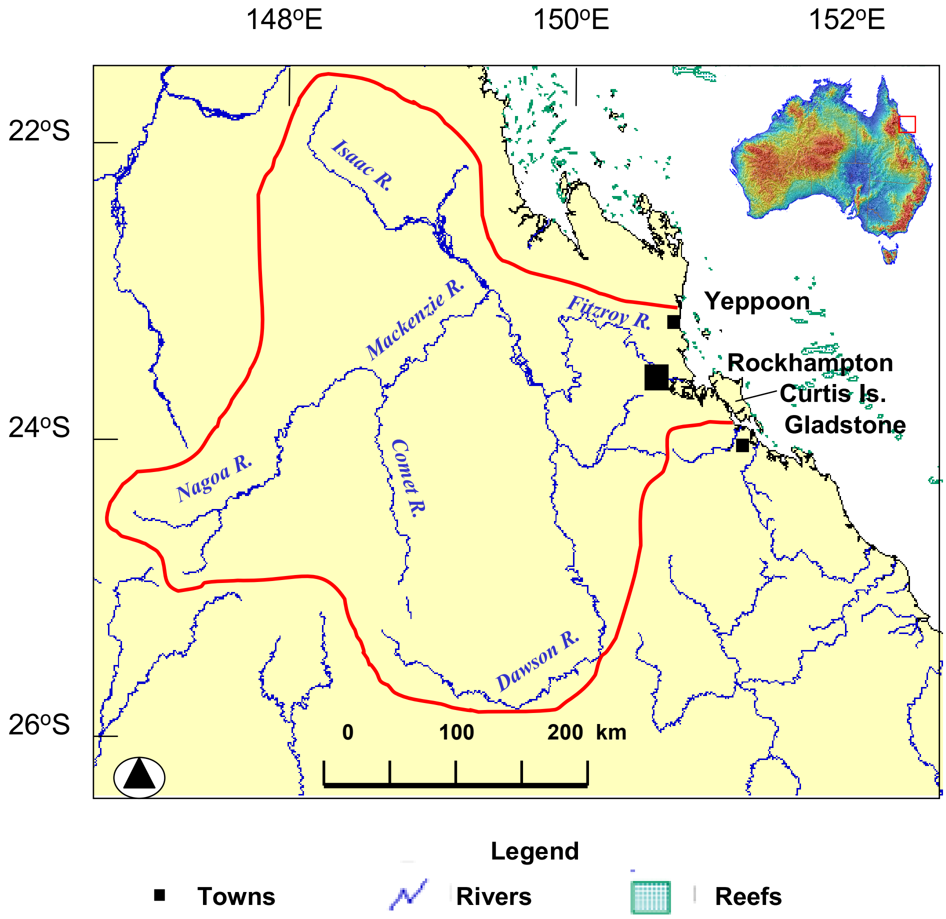


Figure 5.1 Fitzroy River study area (Queensland Fisheries Service, CHRIS website, March 2006). The study area covers land and inshore areas encompassed by the red line.

Land use

Compared to Princess Charlotte Bay, the Fitzroy River area can be considered to be highly modified by human activity. The majority of the area is developed for grazing (125 680 km^2) and cultivation (7 109 km^2). The remainder is state forest and timber reserves (10 506 km^2) and national park (3 380 km^2). Significant land clearing for grazing and cropping has resulted in woody weed invasion, erosion and salinity problems, while pollution from mining and industrial development, particularly in the Curtis area near Gladstone, threatens the local ecosystems and fisheries (DPI 1993). The Fitzroy River delta is the site of recreational and commercial fishing and crabbing, salt production, rail and shipping transport infrastructure and extensive grazing (ANCA 1996). Surrounding areas are also impacted by urban development, selective logging and industrial development (ANCA 1996). The floodplains of the Fitzroy River to the north and west of Rockhampton have been heavily cleared and modified for grazing and urban development and very little original vegetation remains (ANCA 1996). Numerous water storages have been constructed throughout the Fitzroy and Curtis coast catchments including the Awonga Dam to provide urban and industrial water for Gladstone, and the Fairbairn Dam in the Fitzroy catchment to supply water for the Emerald Irrigation Area. All of the major rivers in the region, except the Isaac, have multiple weirs (DPI 1993). A number of the fauna in the region are endangered due to land use changes, and diminished catches of barramundi have been reported downstream from the Fitzroy River barrage at Rockhampton relative to pre-construction catches (DPI 1993). The sediment load deposited into the marine environment via the Fitzroy catchment has been estimated at 1.86 million tonnes per annum (Moss, Rayment *et al.* 1992).

Estuaries and coastal zone

Despite these changes, the floodplains to the north and west of Rockhampton still include significant seasonal lagoons and billabongs, permanent and seasonal swamps and the river channel. Between the mainland and Curtis Island significant near-pristine wetlands still survive in a number of inlets (Auckland and Colosseum), creeks (Cawarral and Pumpkin) and rivers (Calliope and Boyne) (Quinn and Garrett 1992). These areas, and the estuary of the Fitzroy River, have mangrove forests (380 km^2), saltmarsh (319 km^2) and floodplain. Extensive seagrass beds are also found in the area (Lee Long, Coles *et al.* 1992). The Fitzroy River delta covers an area of 703 km^2 and includes seasonal and permanent estuarine and freshwater swamps and lagoons, woodland and sedgelands, mangrove forests, and intertidal sand and mud flats (ANCA 1996). Tidal range is medium (4.1 – 10.0 m) (Bucher and Saenger 1991).

Climate

The climate of the Fitzroy area is sub-tropical. Most of the rainfall occurs in the summer months (January – March) as it does in Princess Charlotte Bay. Rainfall across the region is highly variable and ranges from an annual mean maximum of about 1 800 mm in the coastal ranges down to 500 mm in the western areas (DPI 1993). As in the north, the south-east trade winds dominate the region throughout the year and cloudiness is at a maximum in the summer months (Downey 1983). Air temperatures range from a mean maximum of 32°C in December down to a mean minimum of 9°C in July (Clewett, Clarkson *et al.* 2003). Like Princess Charlotte Bay, the estuarine areas of the Fitzroy River area are classified as 'low rainfall' (Bucher and Saenger 1991).

Barramundi habitat

Originally supporting the largest freshwater barramundi populations in the state, commercial and recreational catch along the Fitzroy coast has been significantly reduced due to land use change and construction of the Fitzroy River barrage (Midgley 1987). However, catch is still considered substantial – a reflection of the extensive wetland, estuarine and riverine habitats in the area that still remain (Quinn and Garrett 1992). Table 5.1 gives a comparison of the two study areas.

Table 5.1 A comparison of the Princess Charlotte Bay and Fitzroy River study areas.

Parameter	Princess Charlotte Bay	Fitzroy River area
Catchment area (km^2)	50 000	142 645
Nursery habitat area (km^2)	3 920	898
Mean minimum July temperature (°C)	13	9
Mean maximum December temperature (°C)	35	32
Mean annual rainfall (mm)	1 133	848
Mean annual flow (Ml)	1 372 334	3 966 067
Sea surface temperature (°C)	24 – 30	20 – 30

5.3 DATA

Commercial fisheries logbook (CFISH) data

As in the short-term climate analyses for Princess Charlotte Bay, monthly catch and effort data were extracted from the Queensland Department of Primary Industries and Fisheries CFISH database, for grid squares corresponding to the Fitzroy River estuary and narrows (R28, R29, R30, S29) for the financial years 1989/90 – 2002/03 (Figure 5.2). Total annual financial year barramundi catch and effort data for the grid points selected were plotted for the years available (Figure 5.3) and show, in contrast to Princess Charlotte Bay, a significant coefficient of determination (R^2 = 0.78). For this reason, as in the analysis of Princess Charlotte Bay data, catch adjusted for effort (CAE) was calculated and used in the correlative analyses. Fingerlings have been stocked in a number of habitat areas in the region since 1992, and various changes to management and marketing arrangements may have affected patterns of fishing (Robins, Halliday *et al.* 2005).

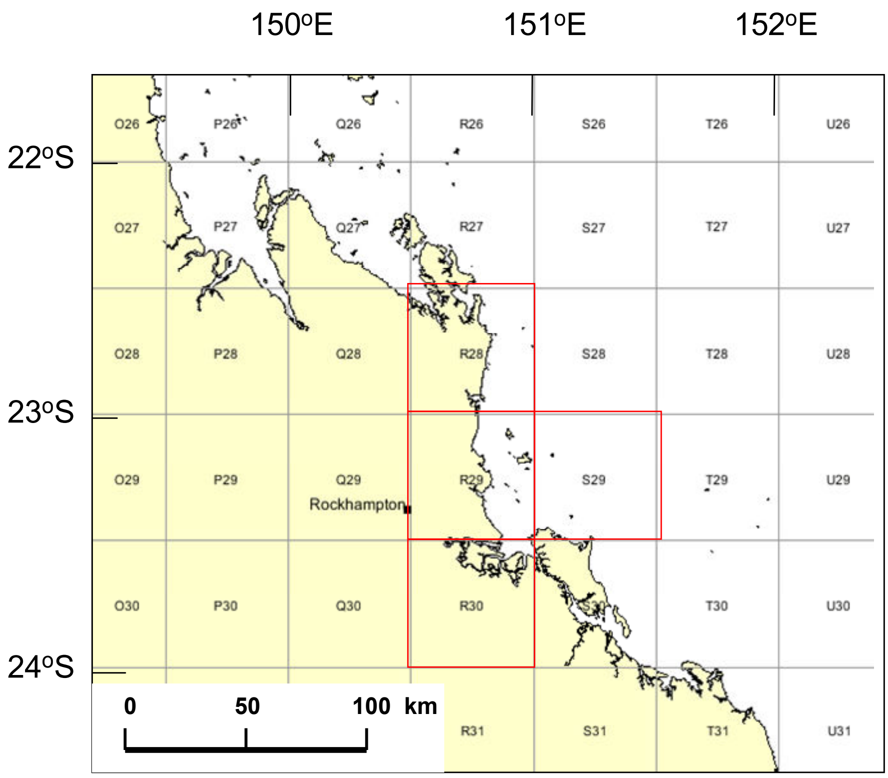


Figure 5.2 CFISH grid squares for the Fitzroy River study area (Queensland Fisheries Service, CHRIS website, March 2006).

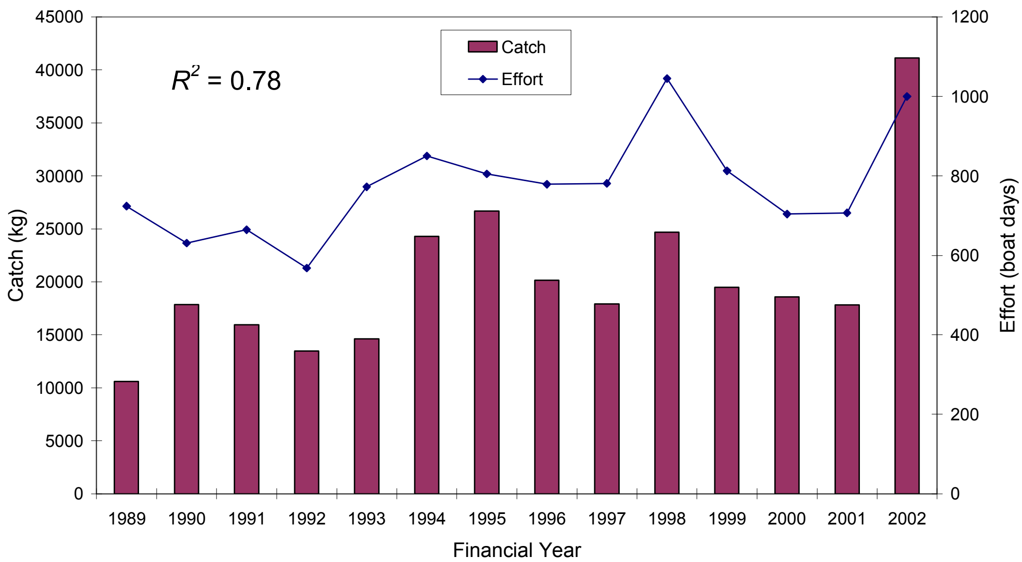


Figure 5.3 Annual financial year CFISH barramundi catch (bars) and effort (line) for the Fitzroy River area (1989/90 – 2002/03).

Climate Data

Climate data for the Fitzroy River area was collated from a number of sources as outlined below for the period of barramundi catch data and including lags of up to five years.

Rainfall

In the Fitzroy River area, rainfall is recorded by the BOM at Bajool (23°39'S 150°39'E), Mt Morgan (23°38'S 150°23'E), Mt Larcom (23°49'S 150°59'E), Rockhampton (23°23'S 150°28'E), Pt Alma (23°35'S 150°50'E), Langmorn (23°50'S 150°45'E), Raglan (23°43'S 150°49'E), Stanwell (23°29'S 150° 20'E) and Gracemere (23°26'S 150°27'E). Average area monthly rainfall was calculated, as for Princess Charlotte Bay, as a measure of coastal rainfall. In the case of the Fitzroy, coastal rainfall may be significantly different to rainfall in other areas of the basin, and in some cases does not coincide with freshwater flow events due to the spatial variability of rainfall in the region and size of the basin (Robins, Halliday *et al.* 2005). For the exploratory analysis, rainfall records from Yaamba were used.

Freshwater flow

Monthly freshwater flow data were taken from the Queensland Department of Natural Resources and Water (QDNRW) stream gauge database (see p.48). In the Fitzroy River, data for the most downstream gauge currently in use "the Gap" were selected (Station number: 130005A; 23 °05'S 150 °06'E; commence 30/04/1964). Measurements include extractions upstream and influences from the barrage.

Terrestrial air temperature and evaporation

Interpolated maximum and minimum monthly average terrestrial air temperature and monthly total pan evaporation data were extracted from the BOM SILO database for a grid point aligned to the mouth of the Fitzroy River and Kepple Bay (23°30'S 150°48'E).

Sea surface temperature (SST)

As was the case in Princess Charlotte Bay (see p.52), there are no long-term, in-situ recordings of SSTs in the Fitzroy River estuary or Kepple Bay and so data were taken from the NASA PO.DAAC web site. Monthly averaged SST data was extracted for a one degree grid box in Kepple Bay (23°S 151°E).

Indices of the Southern Oscillation (SOI)
Monthly average values of the SOI were the same for the Fitzroy region as in the analyses for Princess Charlotte Bay.

Indices of the Madden Julian Oscillation (MJO)
Phases 4, 5 and 8 of the MJO were used in these analyses. These phases correspond to a significant enhancement, suppression and suppression of rainfall respectively in the Fitzroy River area over the November – March period (Wheeler and Hendon 2004).

Although the climate of the Fitzroy River area is defined as sub-tropical, in most years the majority of rainfall occurs in the months aligning to the northern wet season and so the seasonal grouping of data used in the Princess Charlotte Bay analyses was maintained: pre-wet (October – December), wet (January – March), early dry (April – June) and dry (July – September). Table 5.2 is a summary of the final list of variables used in the Fitzroy River area analyses.

5.4 METHODS

The methodology used in the Fitzroy River area follows that outlined in Chapter 4 for the analyses of short-term climate effects on commercial barramundi catch in Princess Charlotte Bay.

Hypotheses
Influences from climate on barramundi CAE in the Fitzroy River area would be expected to be similar to those seen in Princess Charlotte Bay except for a number of complicating factors in such a modified area. As reviewed in section 5.2, changes to the area include the construction of the Fitzroy River barrage, subsequent alterations to the fish ladder, changes to the hydrology of the river system after the 1991 flood, draining of wetlands and clearing of the catchments for agricultural and other land uses, development and pollution in the estuarine reaches, and changes in the management of the fishery. Some of these changes would be expected to alter freshwater flows and the suitability and extent of nursery habitats and so climate variables that in Princess Charlotte Bay were a measure of a suitable nursery habitat (rainfall, freshwater flow and

evaporation), might not return such a strong correlation in the Fitzroy River area. Spawning success as affected by SSTs would not be expected to be influenced by anthropogenic changes.

Slight differences in the climate of each area might also affect the results. The mean December maximum air temperature in the Fitzroy River area was lower (3 ^{o}C) than that in Princess Charlotte Bay. However, maximum air temperature was not a climate variable that significantly affected the survival of young fish in Princess Charlotte Bay and so it is not likely to be a limiting factor in the Fitzroy River area either. The mean minimum July air temperature in the Fitzroy River area was also somewhat lower than in Princess Charlotte Bay (4 ^{o}C) and as the region is close to the southern extreme of the species range, the effect from minimum air temperatures may be significant in the Fitzroy River area.

Unfortunately, impacts from climate on the early life cycle stages of fish in the Fitzroy River area are impossible to differentiate from impacts to the later life cycle stages as catch is the only measure of population biomass. Variables that were predicted to be affected by anthropogenic influences are highlighted in the amended hypothesis (Table 5.3). As there is some evidence in the literature that, due to the cooler conditions, growth rates of barramundi residing in the Fitzroy River area may be slower than those in Princess Charlotte Bay (e.g. Staunton-Smith, Robins *et al.* 2004), it was hypothesised that significant climate effects corresponding to the development of critical nursery habitats may be at a longer lag to catch than in the north.

Table 5.2 Data used in the analyses of short-term climate effects on the Fitzroy River area barramundi fishery noting transformations undertaken prior to analysis.

Variable	Source	Format	Notes	Transformations
Barramundi catch adjusted for effort	CFISH database	Financial year total catch	Sum of 4 grids	Untransformed
Madden Julian Oscillation (MJO)	BMRC	Count of days in each phase for November - March	Phases 4, 5 and 8	Untransformed
Southern Oscillation Index (SOI)	QDPI&F and QDNRW Long Paddock website	Average seasonal SOI value	Base period 1887-1989	Untransformed
Freshwater flows	QDNRW Stream gauge site	Total season catchment flow	Gap gauge station	Log Natural +1
Rainfall	BOM SILO database	Total seasonal rainfall	Average of 8 stations	Cubed Root
Maximum air temperature	BOM SILO database	Average monthly maximum	Representative grid	Log Natural +1
Minimum air temperature	BOM SILO database	Average monthly minimum	Representative grid	Log Natural +1
Evaporation	BOM SILO database	Total annual evaporation	Representative grid	Log Natural +1
Sea surface temperatures (SST)	NCEP	Seasonal average	Representative grid	Untransformed

CFISH = Queensland Commercial Fisheries Database System; BOM = Bureau of Meteorology; BMRC = Bureau of Meteorology Research Centre; QDNRW = Queensland Department of Natural Resources and Water; QDPI&F = Queensland Department of Primary Industries and Fisheries; NCEP = National Centre for Environmental Prediction (United States).

Table 5.3 Hypothesis linking climate variability and commercial barramundi catch for the Fitzroy River area. As in the Princess Charlotte Bay area, conditions that are expected to correlate with an increased year-class size and/or subsequent catch are indicated by a "+" sign while those that are expected to decrease year-class size and/or resulting catch are indicated by a "–" sign. Climate parameters that are not linked in the life cycle model to the developmental stage of the fish are marked as not applicable (n/a). Those effects that are expected to be affected by anthropogenic impacts to the area are highlighted in grey.

Climate variable \ Life cycle stage	Spawning	Larvae	Fingerlings	Juveniles	Maturing males	Returning males
Minimum terrestrial air temperature	n/a	+	+	+	+	n/a
Maximum terrestrial air temperature	n/a	+	+	+	+	n/a
Rainfall	n/a	n/a	+	+	+	+
Freshwater flow	-	+	+	+	+	+
Evaporation	n/a	-	-	n/a	n/a	n/a
Sea surface temperature	+	+	n/a	n/a	n/a	n/a
MJO Phase 4	n/a	+	+	+	+	+
MJO Phase 5	n/a	-	-	-	-	-
MJO Phase 8	n/a	-	-	-	-	-
Average Jul-Sept SOI	n/a	+	+	+	+	+
Average Oct-Dec SOI	n/a	+	+	+	+	+
Average Jan-Mar SOI	n/a	+	+	+	+	+
Average Apr-Jun SOI	n/a	+	+	+	+	+

5.5 RESULTS

Exploratory analysis

As with the Princess Charlotte Bay analyses, an initial step for Fitzroy River area was to plot the barramundi catch data against the long-term rainfall of the region – in this case as measured at Yaamba (Figure 5.4). Again, the years of the study were highlighted to give an indication of the range of climate variability observed during the study period, and trends in the data were indicated by a line of best fit.

The range of climate variability as measured by rainfall in the Fitzroy River area was well captured by the years of the study and included the third wettest and the seventh driest year in the past 104 years (i.e. the highest and lowest decile respectively in recorded history). Rainfall for the central Queensland region is less than that for Princess Charlotte Bay – an average of 848 mm as opposed to 1133 mm. Additionally, the trend in long-term rainfall for the century is different for each region – increasing in Princess Charlotte Bay and decreasing in the Fitzroy River area. A scatter plot of each climate variable versus catch was generated to identify any obvious relationships (Appendix 4).

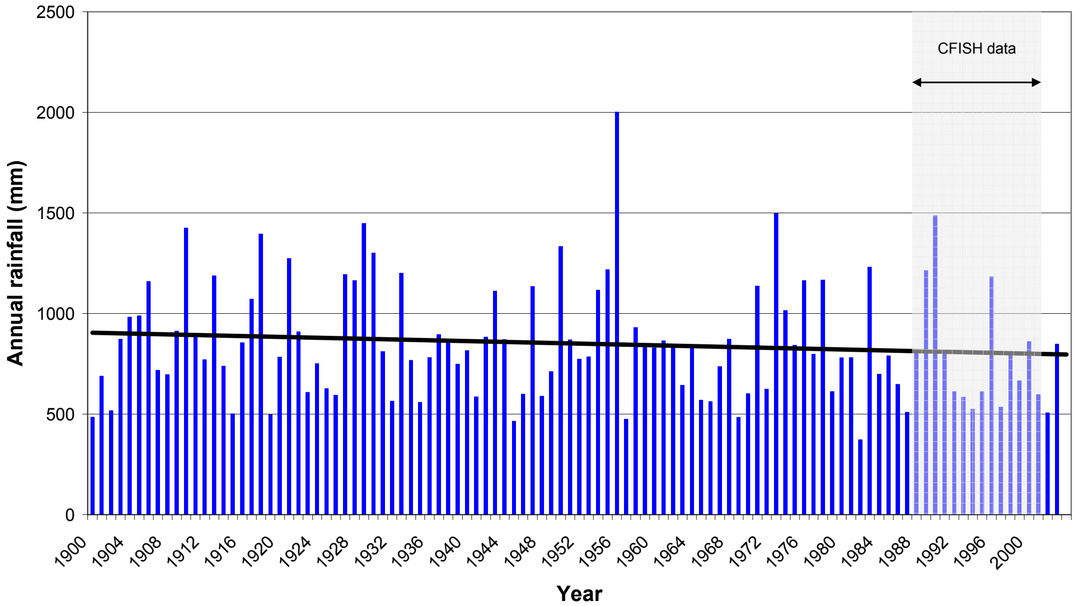


Figure 5.4 Annual rainfall at Yaamba in the Fitzroy River area (1900 – 2004) (Australian Rainman). Plot indicates variability, trend (line) and the period of corresponding barramundi CFISH data (shaded).

Correlation matrix

As in Princess Charlotte Bay, a correlation matrix of climate parameters was generated to identify any collinearity in the Fitzroy River area (Table 5.4). There were a number of correlated variables including evaporation, rainfall and flow for a number of seasons, and the October – December SOI and rainfall ($r = 0.56$; $p < 0.05$).

Table 5.4 Pearson coefficient of correlation (r) matrix of climate variables and indices for the Fitzroy River area. Correlations ≥ 0.54 or ≤ -0.54 are significant at the $p < 0.05$ level and correlations ≥ 0.46 or ≤ -0.46 are significant at the $p < 0.10$ level (n=14).

	Max temp Dec	Min temp Jul	Evap Annual	Rainfall Jul-Sept	Rainfall Oct-Dec	Rainfall Jan-Mar	Rainfall Apr-Jun	MJO Phase 4	MJO Phase 5	MJO Phase 8	Av Jul-Sept SOI	Av Oct-Dec SOI	Av Jan-Mar SOI	Av Apr-Jun SOI	Av Jul-Sep SST	Av Oct-Dec SST	Av Jan-Mar SST	Av Apr-Jun SST	Flow Jan-Mar	Flow Apr-Jun	Flow Oct-Dec	Flow Jul-Sep
Max temp Dec	1.00																					
Min temp Jul	-0.19	1.00																				
Evap Annual	0.11	-0.04	1.00																			
Rain Jul-Sept	-0.26	0.66	-0.20	1.00																		
Rain Oct-Dec	-0.24	-0.03	-0.46	-0.23	1.00																	
Rain Jan-Mar	0.29	-0.06	-0.45	0.04	0.29	1.00																
Rain Apr-Jun	0.03	-0.27	0.01	-0.10	-0.23	-0.10	1.00															
MJO Phase 4	-0.47	-0.04	0.17	-0.28	0.12	-0.23	0.07	1.00														
MJO Phase 5	-0.09	0.23	-0.23	0.09	0.13	0.28	-0.23	0.22	1.00													
MJO Phase 8	0.53	-0.18	-0.21	-0.02	-0.05	0.34	-0.04	-0.61	-0.46	1.00												
Av Jul-Sept SOI	-0.21	-0.03	-0.64	0.44	0.41	0.17	-0.01	-0.18	0.26	0.08	1.00											
Av Oct-Dec SOI	-0.62	0.07	-0.56	0.35	0.56	0.08	-0.02	0.12	0.39	-0.30	0.83	1.00										
Av Jan-Mar SOI	-0.50	0.03	-0.20	0.30	0.39	0.03	-0.19	0.37	0.49	-0.48	0.66	0.83	1.00									
Av Apr-Jun SOI	-0.30	0.02	-0.46	0.29	0.13	0.08	0.49	0.05	-0.02	-0.29	0.41	0.47	0.30	1.00								
Av Jul-Sep SST	0.18	0.29	-0.03	0.54	-0.16	-0.02	-0.22	-0.61	-0.18	0.32	0.25	0.06	0.03	0.00	1.00							
Av Oct-Dec SST	0.75	-0.04	0.13	-0.19	0.07	0.19	0.02	-0.35	-0.27	0.42	-0.14	-0.40	-0.29	-0.13	0.50	1.00						
Av Jan-Mar SST	0.34	-0.06	0.48	-0.08	-0.30	-0.32	0.32	-0.39	-0.45	-0.09	-0.39	-0.41	-0.38	0.17	0.27	0.43	1.00					
Av Apr-Jun SST	0.20	-0.16	0.37	-0.35	0.10	-0.27	0.00	-0.30	-0.51	-0.06	-0.41	-0.36	-0.38	0.06	0.04	0.33	0.82	1.00				
Flow Jan-Mar	0.01	0.13	-0.22	0.11	0.52	0.60	-0.58	0.10	0.56	-0.18	0.31	0.32	0.48	-0.15	-0.01	0.05	-0.44	-0.25	1.00			
Flow Apr-Jun	-0.08	0.15	-0.37	0.21	0.18	0.17	0.67	-0.04	0.17	-0.23	0.32	0.32	0.03	0.57	-0.24	-0.13	0.11	-0.07	-0.03	1.00		
Flow Oct-Dec	-0.13	-0.10	-0.61	0.02	0.79	0.49	-0.27	-0.22	0.02	0.29	0.61	0.58	0.37	0.28	0.00	0.00	-0.32	0.03	0.43	0.08	1.00	
Flow Jul-Sep	0.12	0.15	-0.68	0.25	0.34	0.54	-0.03	-0.48	0.29	0.33	0.56	0.42	0.16	0.46	0.18	0.07	-0.20	-0.14	0.21	0.29	0.70	1.00

Lag analysis

Lag correlations between climate variables and barramundi CAE were calculated for up to five years (Tables 5.5 and 5.6). In the year of catch there was only one significant correlation at the $p < 0.05$ level: maximum December temperature (negative). Maximum temperature is not likely to affect catchability and is a variable that was not significant in the Princess Charlotte Bay analysis. At the $p < 0.10$ level, dry season (July – September) flow and rainfall were both significantly and negatively correlated with barramundi CAE (both negative). Neither the SOI nor MJO were significantly correlated with barramundi CAE in the year of catch.

For longer lag times, there were significant correlations between barramundi CAE and minimum temperature in July (negative) and pre-wet season flow (positive) two years prior to catch and average pre-wet season SST three years prior to catch (negative). Four years prior to catch, the MJO phase 4 as a measure of enhanced rainfall (negative), average dry season SST (positive) and pre-wet season flow (positive) were all significantly correlated with barramundi CAE. Five years prior to catch wet season and early dry season SST were both positively correlated with barramundi CAE, and there was a significant negative correlation between CAE and both dry season rainfall and wet season average SOI (Table 5.5 and 5.6).

Table 5.5 Pearson coefficient of correlation (r) between Fitzroy River area barramundi CFISH catch adjusted for effort (1989/90 – 2002/03) and climate variables (zero – five year lag). Highlighted correlations significant at the $p < 0.05$** and $p < 0.10$* levels.

Variable	0 lag	1 year lag	2 year lag	3 year lag	4 year lag	5 year lag
Minimum temperature Jul (°C)	0.25	0.22	-0.55**	-0.43	-0.11	0.39
Maximum temperature Dec (°C)	-0.61**	-0.32	0.27	-0.02	0.32	-0.27
Rainfall Jul-Sep (mm)	-0.47*	-0.43	0.13	0.07	0.30	-0.47*
Rainfall Oct-Dec (mm)	-0.10	-0.01	0.38	-0.34	0.30	0.16
Rainfall Jan-Mar (mm)	0.09	0.05	0.12	-0.35	0.10	0.01
Rainfall Apr-Jun (mm)	-0.24	0.05	-0.29	0.21	-0.33	0.00
Flow Jul-Sep (Ml)	-0.48*	-0.21	0.26	0.04	0.43	-0.28
Flow Oct-Dec (Ml)	-0.22	-0.15	0.51*	-0.45	0.46*	-0.06
Flow Jan-Mar (Ml)	0.30	-0.15	0.01	-0.19	0.24	0.04
Flow Apr-Jun (Ml)	-0.43	-0.17	-0.11	0.20	0.01	0.17
Evaporation Annual (mm)	0.30	0.21	-0.32	-0.23	-0.32	0.20
Average Jul-Sep SST	-0.06	-0.23	-0.14	0.00	0.80**	-0.37
Average Oct-Dec SST	0.19	0.20	-0.45	-0.64**	0.21	0.20
Average Jan-Mar SST	0.15	0.20	-0.19	-0.33	-0.05	0.59**
Average Apr-Jun SST	0.24	-0.05	0.13	-0.28	-0.15	0.71**

Table 5.6 Pearson coefficient of correlation (*r*) between Fitzroy River area barramundi CFISH catch adjusted for effort (1989/90 – 2002/03) and climate indices (zero – five year lag). Highlighted correlations significant at the $p < 0.05$** and $p < 0.10$* levels.

Variable	0 lag	1 year lag	2 year lag	3 year lag	4 year lag	5 year lag
MJO Phase 4	0.15	0.39	0.17	0.09	-0.57**	-0.15
MJO Phase 5	-0.01	0.28	0.11	0.30	0.02	0.04
MJO Phase 8	-0.17	-0.14	-0.30	-0.15	0.41	-0.32
Average Jul-Sept SOI	-0.28	-0.31	0.31	0.02	0.34	-0.28
Average Oct-Dec SOI	-0.30	-0.14	0.45	0.24	0.33	-0.35
Average Jan-Mar SOI	0.00	0.07	0.38	0.08	0.08	-0.48*
Average Apr-Jun SOI	-0.27	-0.16	0.18	0.35	-0.03	-0.07

5.6 DISCUSSION

Results from the analyses of climate effects on barramundi catch in the modified catchments of the Fitzroy River area are quite different to those in the near-pristine Princess Charlotte Bay area. In the Fitzroy River area, significant correlations between climate parameters and barramundi CAE were inconsistent, and often both positive and negative across the years corresponding to the life span of the fish (for the same variable). Additionally, there were fewer significant correlations between climate and barramundi CAE for the Fitzroy River area compared to Princess Charlotte Bay.

Barramundi in the Fitzroy River area are known from tagging and age structure studies to enter the commercial fishery at two or more years of age. The majority of commercially caught fish are three years old (Staunton-Smith, Robins *et al.* 2004). There was only one significant correlation between a climate variable and barramundi CAE three years prior to catch when it could be expected that the majority of fish were spawned: pre-wet season (October – December) SST. In comparison, there were five significant correlations corresponding to the year of spawning in the Princess Charlotte Bay area. In addition, the relationship between pre-wet season SST and barramundi CAE in the Fitzroy River area was negative – a result that goes contrary to the life cycle model and the result in Princess Charlotte Bay. As barramundi eggs are temperature sensitive, successful spawning usually occurs in water ranging between 27^{o}C and 33^{o}C (Fishbase 2005; Garrett, Mackinnon *et al.* 1987). Inshore SSTs for each region fluctuated between 20^{o}C – 30^{o}C annually and 25^{o}C – 30^{o}C during the pre-wet and wet seasons when fish are spawning. The significant negative correlation with pre-wet season SSTs would indicate that temperatures are too hot for egg or juvenile survival which would not appear to be the case. In Princess Charlotte Bay where wetlands are very shallow, maximum temperatures in December were higher (31^{o}C – 35^{o}C) and yet did not have a significant negative impact on barramundi CAE. No other climate parameter was significantly correlated with pre-wet season SST and so collinearity is not the cause of the significant correlation with barramundi CAE. The relationship between barramundi catch and SSTs in the Fitzroy River area has not been studied elsewhere and so higher order influences including interactions between predators and primary productivity that are not yet understood may explain the result. Alternatively, it may be that the correlation is spurious or distorted by anthropogenic influences on the fishery, either at the time of spawning, or later in the life cycle of the fish.

Two variables were significantly correlated with barramundi CAE in the Fitzroy River area two years prior to catch (the lag corresponding with earliest entry into the commercial fishery). The first, minimum air temperature in July, was negatively correlated with barramundi CAE – a result that once again goes contrary to the life cycle model but in this case is similar (although not significant) to Princess Charlotte Bay as well. The minimum temperature in each area during July drops below 20^{o}C (the temperature at which feeding in adults has been recorded to cease, and below which adult mortalities in the Fitzroy River have been observed (Agcopra, Balston *et al.* 2005; Robins, Halliday *et al.* 2005)), and so is considered cold enough to affect the survival of juveniles. However, lower temperatures and lower subsequent catch would produce a positive correlation and not negative as seen here. As the variable used in the analysis was terrestrial air temperature and not river or creek water temperature, there may be a difference between the two. However, research both overseas and in Australia has shown that for air temperatures above freezing there is a significant positive linear relationship between river and air temperature (Barlow and Lisle 1987), a finding confirmed in a study of aquaculture ponds in the Cairns area (Agcopra, Balston *et al.* 2005). This result would suggest that although air and water temperatures may not be identical, the sign of the relationship with barramundi CAE should be the same. It could be that predation on barramundi is reduced in cooler temperatures and so more cohorts survive through to the commercial fishery. Higher order relationships such as these have been observed in riverine ecosystems overseas (e.g. Livingston 1997). Research into the feeding habits of known predators including birds and crocodiles would perhaps clarify if there is a causal link in this study.

The other climate variable that was significantly correlated with barramundi CAE two years prior to catch was pre-wet season flow. As in Princess Charlotte Bay, it is likely that pre-wet season flow is enhancing barramundi habitat and/or driving increases in primary productivity as seen in studies of other estuarine species (e.g. Sobrino, Silva *et al.* 2002). Freshwater flow at this time of the year is much more variable than flow during the wet season and would break the dry season if levels were high enough to exceed the barrage. For these reasons it could be expected that pre-wet season flow may have a greater impact on catch variability than the less variable wet season flows that showed a positive but non-significant correlation with barramundi CAE. It is likely that the inconsistent and non-significant correlations between freshwater flow in other seasons and barramundi CAE over the five years is the result of modifications to flow in the area.

In the year of catch, dry season rainfall and flow were each negatively and significantly correlated with barramundi CAE in the Fitzroy River area, although, not significantly correlated with each other. Neither rainfall nor flow at this time of year is high, and so again neither would be expected to affect commercial catch. These variables were not significant in the Princess Charlotte Bay area in the year of catch, and in a study by Meynecke, Lee *et al.* (2006), correlations between dry season (in this case May – October) barramundi catch and concurrent rainfall in the central Queensland region were not significant. In contrast, results of a study by Robins, Halliday *et al*. (2005) found a significant correlation between annual barramundi CAE and both summer (December – February) flow and rainfall in the year of catch. It could be that the difference in seasons, or variations in the data sets used, may explain the discrepancies in correlations. Such varied results highlight the tenuous link between climate and catch in this area.

The significant negative correlation between barramundi CAE and maximum December temperature in the year of catch is also contrary to the life cycle model. December temperatures are not expected to affect catchability of barramundi and so the result may be spurious. In Princess Charlotte Bay maximum air December temperature was significantly and negatively correlated with pre-wet season rainfall, pre-wet season and early dry season freshwater flow, and positively correlated with annual evaporation, variables that in most cases were also significantly correlated with barramundi CAE. This collinearity between variables is a likely reason for a significant correlation between barramundi CAE and maximum December air temperature in Princess Charlotte Bay. However, in the Fitzroy River area maximum December air temperature was not significantly correlated with any other terrestrial climate variable. Other climate variables such as wind speed and direction may be both correlated with maximum December temperatures and barramundi CAE and so explain the correlation with catchability, but were not considered in this study.

Evaporation, a variable that was strongly correlated with subsequent catch in the Princess Charlotte Bay area was not significant in the Fitzroy River area at any lag. The correlations between barramundi CAE and wet season evaporation two and three years prior to catch were higher than for annual evaporation (also the case in Princess Charlotte Bay), but still not significant at the $p < 0.10$ level. Nursery areas in the Fitzroy River area differ from those in the north and might explain the lack of correlation between evaporation and CAE. In Princess Charlotte Bay, the primary barramundi nursery habitats are shallow, rain-fed wetland swamps. However, in the Fitzroy the dominant habitat is thought to be tidally influenced estuarine mangrove fringes, saltpan and small feeder creeks. As a result, in the Fitzroy River area tides would have a more significant impact on these areas than evaporation. It could also be that the relationship is not clear due to anthropogenic alterations to wetland habitats.

Cases of collinearity between the SOI and maximum temperature in December, annual evaporation and pre-wet season rainfall in the Fitzroy River area were significant and consistent with those in the north. However, none of the climate indices (SOI of MJO) were significantly correlated with barramundi CAE for lags of up to three years in the Fitzroy River area. The few significant correlations between barramundi CAE and other climate variables four and five years prior to catch do not reinforce results found in Princess Charlotte Bay, are sporadic, inconsistent in sign and occur prior to spawning for the majority of commercially caught individuals. For these reasons they are considered spurious.

To summarise, apart from pre-wet season flow two years prior to catch, there are no other significant correlations between climate and barramundi CAE in the Fitzroy River area that concur with the life cycle model during the three year growth period to commercial size (Table 5.7). As there are a number of discrete genetic barramundi strains around Australia (Shaklee, Salini *et al.* 1993), it can be assumed that the species has evolved to suit the range of climatic conditions observed at each study area (Meynecke, Lee *et al.* 2006). Most of the latitudinal differences between the study areas, then, are likely to have been compensated for by adaptation in the species (Neil Gribble, Fisheries Research Scientist, QDPI&F, pers. comm. November 2006) and so fewer significant correlations between climate and barramundi CAE in the Fitzroy River area would suggest that anthropogenic changes to the habitat have, as hypothesised, interfered with or masked the relationships between climate and the fishery in this modified area.

As the barramundi is highly fecund, and virtually without predator as an adult (Davis 1984), disruptive impacts from human intervention on the early life cycle stages are most likely to have the greatest impact on subsequent catch (Johnston 2004; Staunton-Smith, Robins *et al.* 2004). Impediments to the natural river flow will reduce freshwater in the estuarine areas, and possibly alter the timing of flow events that do occur. Changes to nursery habitats no doubt affect the extent and productivity of the fishery, and stocking fish into rivers introduces cohorts that are not subjected to the variations of climate in the critical early life cycle stages. Stocking in the Fitzroy has occurred since 1992 and is both inconsistent in timing and the numbers of fingerlings released. Each of these factors has the capacity to mask the climate signal in subsequent catch, especially when compounding effects over the life cycle of the fish are considered. Certainly, the results of these analyses would indicate that anthropogenic changes to catchments and nursery habits mask or alter the relationship between barramundi catch and climate when compared to the results in Princess Charlotte Bay.

Table 5.7 Summary of findings from the correlation analyses between short-term climate parameters and Fitzroy River area barramundi catch compared to the hypothesis presented in Table 5.3. Parameters that were expected to correlate with increased population and therefore catch are indicated by a "+" sign while those that were expected to decrease survival and resulting catch are indicated by a "–" sign. Climate variables that are not linked in the life cycle model to the developmental stage of the fish are marked as not applicable (n/a). Correlations that were significant at the $p < 0.10$ level and confirm the original hypothesis are shaded in grey. Correlations that were not significant are not highlighted, those that were significant and opposite in sign to that predicted are hatched .

Climate variable \ Life cycle stage	Spawning	Larvae	Fingerlings	Juveniles	Maturing males	Returning males
Minimum terrestrial air temperature	n/a	+	+	+	+	n/a
Maximum terrestrial air temperature	n/a	+	+	+	+	n/a
Rainfall	n/a	n/a	+	+	+	+
Freshwater flow	-	+	+	+	+	+
Evaporation	n/a	-	-	n/a	n/a	n/a
Sea surface temperature	+	+	n/a	n/a	n/a	n/a
MJO Phase 4	n/a	+	+	+	+	+
MJO Phase 5	n/a	-	-	-	-	-
MJO Phase 8	n/a	-	-	-	-	-
Average Jul-Sept SOI	n/a	+	+	+	+	+
Average Oct-Dec SOI	n/a	+	+	+	+	+
Average Jan-Mar SOI	n/a	+	+	+	+	+
Average Apr-Jun SOI	n/a	+	+	+	+	+

5.7 CONCLUSION

Analyses were undertaken in the Fitzroy River area to determine if anthropogenic modifications to barramundi habitat have masked or altered the climate signal in catch. In contrast to the results in Princess Charlotte Bay, correlations between climate parameters and subsequent barramundi CAE in the Fitzroy River area were inconsistent, less significant and often contrary to the life cycle model. Only one variable (pre-wet season freshwater flow two years prior to catch) was significantly correlated with barramundi CAE and fitted with the life cycle model of the species. As in Princess

Charlotte Bay, flow at this time of year is probably breaking the dry season drought, providing nutrients and extending barramundi habitat. No other variable consistent with the life cycle model was significantly correlated with barramundi CAE. This result, and the inconsistent nature of climate and catch relationships across the years of the study, would indicate that anthropogenic effects have distorted the signal from climate in the Fitzroy River area, and without an understanding of these effects it is risky to assume results are transferable from one region to another.

CHAPTER 6: EXTREME AND THRESHOLD CLIMATE EVENTS

6.1 INTRODUCTION

There is some evidence to suggest that extreme climate events may impact on the north-east Queensland barramundi fishery in non-linear ways. In the Fitzroy region, significantly higher catches were observed in response to summer freshwater flow events that exceeded 1.4 Ml (Sawynok 1998), and larger year-class sizes when flows were highest (Staunton-Smith, Robins *et al.* 2004). This chapter explores the concept of extreme and "threshold" climate events and addresses research question 5 using data from Princess Charlotte Bay: Do extreme events at the short-term time-scale have a threshold or non-linear impact on barramundi catch?

6.2 BACKGROUND

Ecological systems are constantly dynamic and vary in extent, composition and viability at various time scales, a result of influences from both abiotic (non-living) and biotic (living) factors. Over a number of decades research on the impacts of abiotic factors on ecosystems led to the concept of resilience whereby a stable ecosystem can withstand a certain degree of variability before reaching a critical threshold or "breakpoint" after which it will either collapse, or shift into a qualitatively different state (Holling 1973). An extreme example of such a "break point" is when an organism becomes extinct and the ecosystem is changed irreversibly. Less dramatic changes to species assemblages occur when environmental conditions favour one species over another. In this case, the composition, but not the number of species, is altered and the ecosystem attains a new stable state. The system will then require significant pressure to revert it back to the original or to change to another (May 1977).

The change from one stable state to another in response to a climatic event is demonstrated in a fishery by the recently identified oscillation from an "anchovy regime" to a "sardine regime" every 50 years or so in the Pacific basin. This phenomena is believed to be the result of a shift in the ENSO regime and/or the IPO to favour either one species or the other, and includes changes to both air and ocean temperature and carbon dioxide levels (Chavez, Ryan *et al.* 2003; Sandweiss, Maasch *et al.* 2004; Scheffer, Carpenter *et al.* 2001). Regime shifts in freshwater systems have also been observed and include the changes in a lake ecosystem towards a state of eutrophication and algal blooms in response to incremental alterations in the hydrological or nutrient balance (e.g. Holling 1973). Similarly, continuous fishing pressure that selects for some species in the ecosystem and not others can result in a collapse in the selected fish population (Glantz and Feingold 1990; Holling 1973; May 1977). Such a collapse can then change the competition and predation balance within the ecosystem and result in catastrophic changes to species abundance at various tropic levels (Scheffer, Carpenter *et al.* 2001).

Extreme climatic events and other natural disasters can also generate significant ecosystem changes. As an example, tropical cyclones in north-east Queensland impact heavily on rainforest communities (Nott and Hayne 2001) as the shallow rooted, tall rainforest trees are susceptible to uprooting, breakage and defoliation (Primack and Corlett 2005). An increase in drought and fire frequency has also been shown to alter these tropical forest ecosystems with a shift to more sclerophyll species (Kershaw 1985; Mayle, Beerling *et al.* 2004). With respect to barramundi, the survival of early life cycle stages is improved with increased availability and productivity of wetland nursery habitats (Griffin 1995). Such conditions are often the result of an extreme climatic event that exceeds a certain threshold – such as a flood that inundates extensive areas and dramatically increases the area of wetland habitat. At the other end of the scale, the shallow, restricted habitats left at the end of a drought will concentrate fish into limited areas and result in significantly higher levels of predation from other fish and birds, and in some cases a shift in ecosystem structure (Sheaves 2005).

A non-linear response from an ecosystem may, then, be the result of continuous and/or gradual changes in the environment that reach a threshold, or an abrupt and irregular extreme event (Hilbert 2002; Scheffer, Carpenter *et al.* 2001). Incremental changes in the linked climate and ocean system as a result of anthropogenic climate change is expected to trigger currently unquantifiable and possibly sudden changes to ecosystems worldwide (Enfield and Cid-Serrano 2006; Hsieh, Glaser *et al.* 2005). A warmer world is expected to produce more extreme climatic events, including more intense rainfall, tropical cyclones, heatwaves and drought (IPCC 2003). Understanding the likely impacts to an ecosystem from an extreme or threshold event will be a critical step in managing many resources sustainably under an enhanced greenhouse regime (Enfield and Cid-Serrano 2006).

Where fisheries data are available, a threshold event can be pinpointed quantifiably by identifying the non-linear response in the dependant variable (McFarlane, King *et al.* 2000). However, for fisheries a lack of long-term data often limits both the analyses possible and the range of climatic events observed. This limitation has led a number of researchers (e.g. Finney, Gregory-Eaves *et al.* 2002) to advocate the use of palaeoclimatic data in conjunction with a measure of species abundance (in this case lake sediment cores) as a way of extending the instrument records. Although for many fisheries (particularly in Australia) such historical data are not available. In addition, the literature to date gives no consensus methodology for identifying the impact of an extreme or threshold climate event on a fishery. This chapter proposes a methodology for undertaking an analysis of the impacts of extreme and threshold climate events on a fishery via both qualitative and quantitative processes, and then applies it to data from the commercial Princess Charlotte Bay barramundi fishery.

6.3 DATA

The quantitative analysis used the data compiled for the analysis of short-term climate effects in Princess Charlotte Bay (Table 4.4). The qualitative analysis used observed and modelled flow data described in Chapter 4 (Table 4.4), area average rainfall data for Lakefield (14°57’S 144°12’E), and records of tropical cyclone events from the BOM severe weather data set.

6.4 METHODOLOGY

A two-pronged approach using both quantitative and qualitative analyses was used to identify the impact of extreme or threshold climate events on the Princess Charlotte Bay fishery (Figure 6.1). A quantitative analysis of non-linear responses in the fishery can be undertaken for years of available catch data, and qualitative analysis can be used to identify likely impacts from extreme climate events on the species habitat when a longer climate record exists for which there is no fisheries catch data. For the purpose of this study, an extreme climate event is one in the lowest or highest decile (10th percentile) for the defined period (Suppiah and Hennessy 1998), and a threshold event is one after which the relationship between the climate variable and commercial fishery catch is altered in a non-linear way. The following steps were undertaken to identify non-linear events in Princess Charlotte Bay:

Quantitative approach:

1. The scatter plots of barramundi CAE versus climate variables (those that affect the nursery habitat two years prior to catch and those in the year of catch that would affect catchability) were re-examined in order to identify any non-linear responses from the fishery (Appendix 3);
2. Significant linear relationships were tested for quadratic curvature to identify a curve in the relationship between climate and barramundi catch;
3. Significant quadratic relationships were tested for asymptotic curvature to identify a threshold point in the curve;
4. Non-linear relationships (quadratic, asymptotic, bent stick and step) were identified and thresholds quantified.

Qualitative approach:

1. Modelled flow data were re-examined to determine if extreme flow events were modelled accurately;
2. Extreme events were identified from the historic records of flow and rainfall, and the impacts of these were considered in the context of the life cycle model of the fish, changes in habitat, and supplementary data/observation.

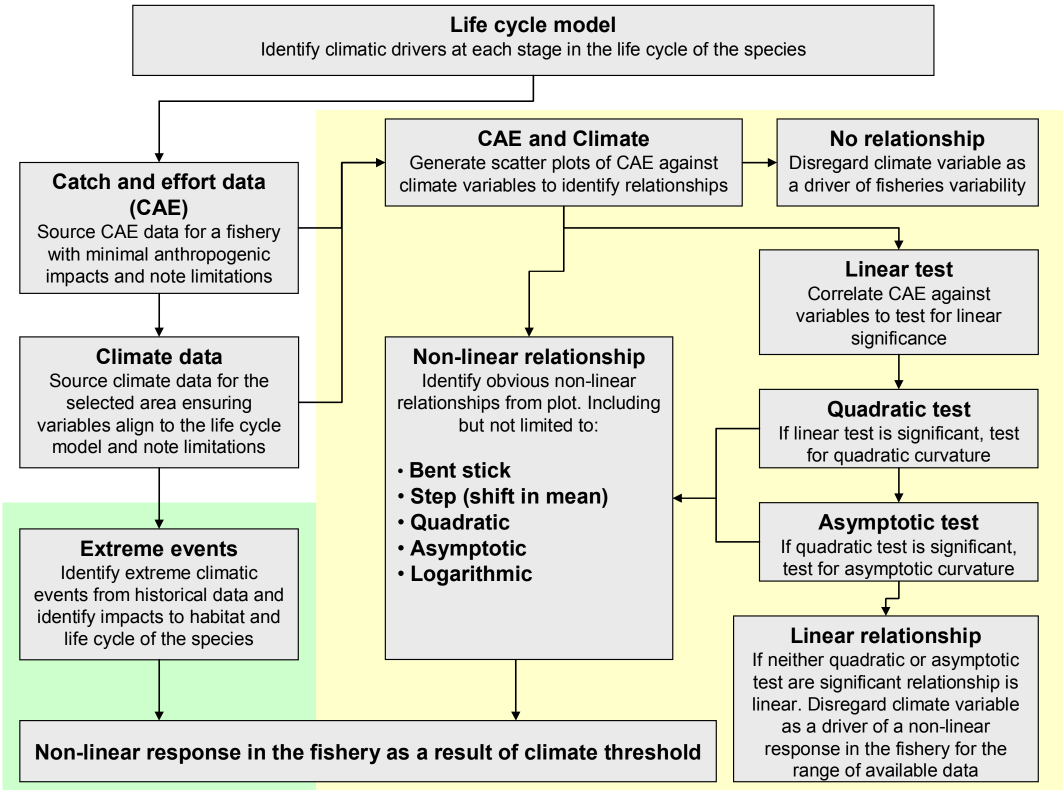


Figure 6.1 Proposed methodology for identifying non-linear, climate driven responses in a fishery. Qualitative analysis is highlighted in yellow and quantitative processes in green.

The model defines three possible outcomes:

1. There is no relationship between the climate variable and fishery catch. In this case the climate variable is not affecting the fishery or the relationship is complex and not discernable from the available data;

2. The relationship between the climate variable and fishery catch is linear, in which case there is no non-linear (threshold) response from the fishery for the available data;

3. There is a non-linear relationship between the climate variable and fishery catch indicating a threshold response from the fishery.

Note that the lack of any clear non-linear relationship between a climate variable and fishery may be because a) the use of synthetic climate data did not accurately model an extreme event that did occur, b) the time series is too short and although the fishery may respond in a non-linear way, for the years of record no threshold events occurred, or c) any non-linear responses from the fishery are perhaps the result of a number of climate variables working together rather than just one (synergistic and/or compounding effects) and so the relationship is not seen clearly when individual variables are examined.

Hypotheses

For the Princess Charlotte Bay area, hypotheses linking barramundi CAE with climate threshold events were generated (Table 6.1). Some thresholds are not spatially dependant (e.g. minimum temperature for survival), while others will be defined by the physical environment (e.g. the quantity of freshwater flow in a river before it exceeds the channel banks, the depth of water evaporated before a wetland habitat dries out). For some variables there may be more than one threshold. For example, temperatures below 20^{o}C are known to significantly increase the mortality of barramundi and so below this threshold the relationship between temperature and catch would be expected to decrease exponentially. A similar response to maximum temperature would be expected once a lethal threshold is reached. A similar relationship would also be expected between SSTs and both spawning success and larvae survival. As the survival of young-of-year barramundi improves in response to an increase in nursery habitat area, it was hypothesised that rainfall sufficient to inundate extensive wetland areas, or a flow event that exceeds the bank of the river, would result in a subsequent increase in catch. However, a flow event that was too high may damage habitats and cause fatalities.

6.5 RESULTS

Quantitative analysis

An initial examination of the scatter plots of Princess Charlotte Bay barramundi CAE and climate variables, both in the year of catch and two years prior to catch, revealed only two obvious non-linear relationships: pre-wet season rainfall and early dry season flow, both two years prior to catch. All remaining plots showed either no relationship or a linear relationship between barramundi CAE and climate.

Table 6.1 Hypothesis linking extreme and threshold climate events and commercial barramundi catch adjusted for effort (CAE) or north-east Queensland. Curves represent the expected relationship between each climate variable and the resulting barramundi catch. Climate variables that are not linked in the life cycle model to the developmental stage of the fish are marked as not applicable (n/a).

Climate variable \ Life cycle stage	Spawning	Larvae	Fingerlings	Juveniles	Maturing males	Returning males
Minimum terrestrial air temperature	n/a					n/a
Maximum terrestrial air temperature	n/a					n/a
Rainfall	n/a	n/a				n/a
Freshwater flow	n/a					
Evaporation	n/a			n/a	n/a	n/a
Sea surface temperature			n/a	n/a	n/a	n/a

Variables identified as having a significant linear correlation to barramundi CAE in Chapter 4 (Table 4.8) were: pre-wet and wet season rainfall and flow in the year of catch, and dry season and wet season rainfall, wet season flow, annual evaporation and wet season SST all two years prior to catch. Obvious non-linear relationships were fitted with a curve and each of the significant linear relationships was tested further for quadratic and asymptotic curvature. Three variables two years prior to catch returned a significantly improved fit when a quadratic model was fitted: pre-wet season rainfall ($R^2 = 0.34$, $p < 0.049$), early dry season flow ($R^2 = 0.34$, $p < 0.507$) (Figure 6.2), and annual evaporation ($R^2 = 0.52$, $p < 0.010$) (Figure 6.3). Each of these variables was then tested for asymptotic curvature. Only evaporation was significant ($R^2 = 0.44$), although, the original quadratic regression explained more of the variance. A downward shift in mean (step function) might also identify the threshold in evaporation as levels above 2 150 mm resulted in below average CAE for all years in the record. However, there were not enough data points to statistically test the observation (Figure 6.3). As per the proposed methodology, variables that had a linear relationship only with CAE, or showed no relationship to CAE, were disregarded as generating a threshold response in the fishery.

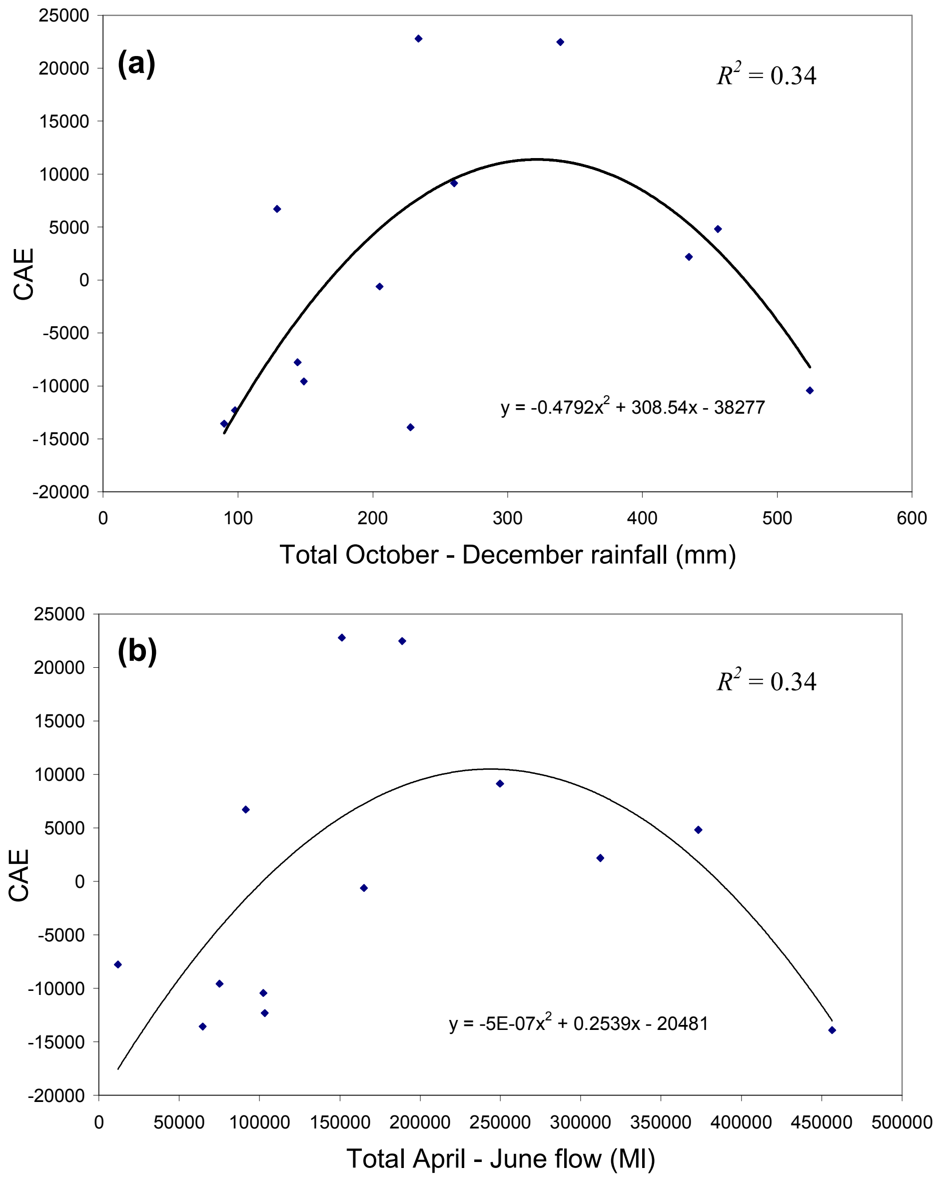


Figure 6.2 Scatter plots of (a) pre-wet season (October – December) rainfall and (b) early dry season (April – June) flow versus Princess Charlotte Bay barramundi catch adjusted for effort (CAE) two years later. Quadratic curves fitted. R^2 values show a significant improvement over the linear correlations.

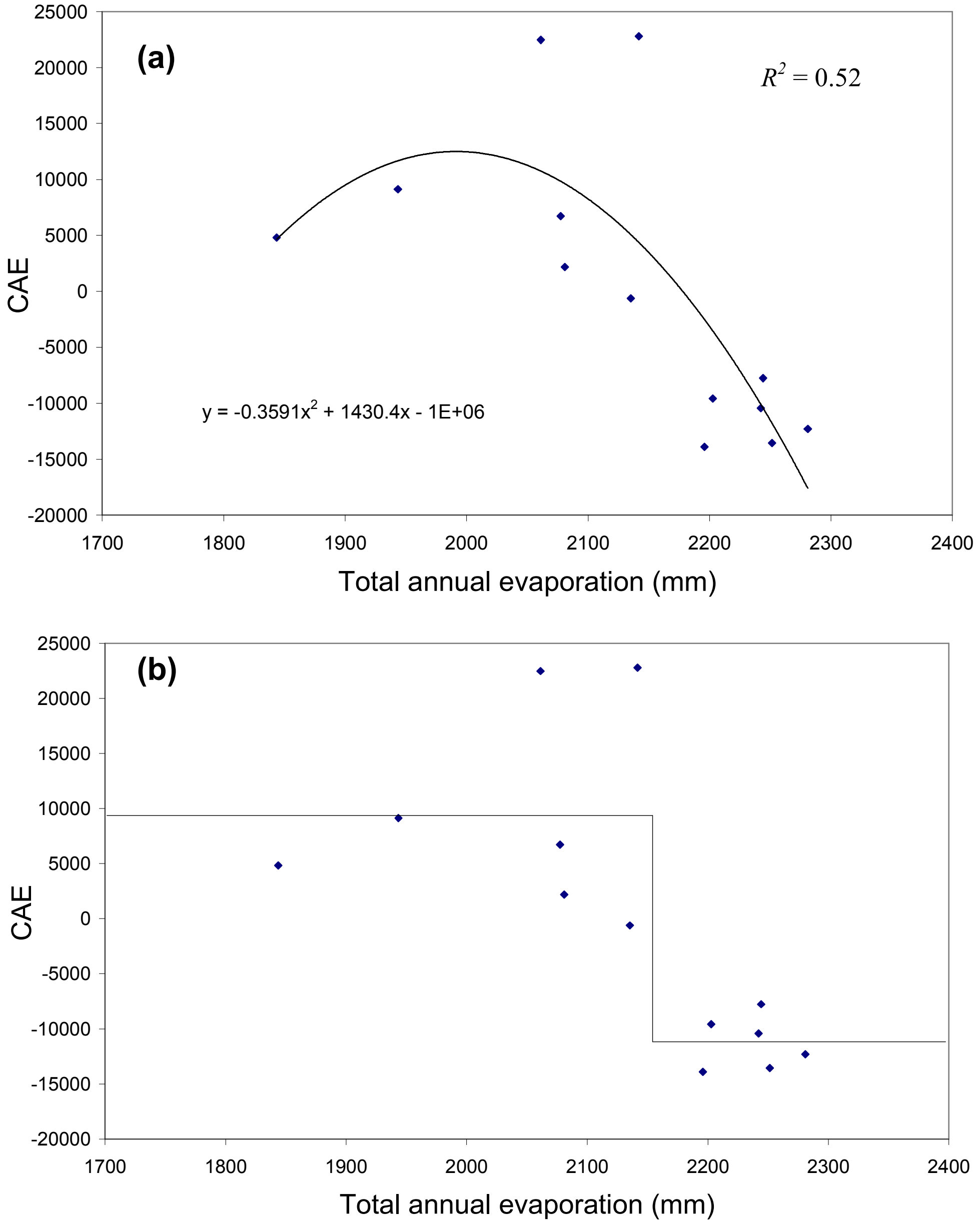


Figure 6.3 Scatter plot of annual evaporation versus Princess Charlotte Bay barramundi catch adjusted for effort (CAE) two years later a) quadratic curve fitted and b) step function. The R^2 values for the quadratic function show a significant improvement over the linear correlations. There are insufficient data points to calculate an R^2 value for the step function.

Qualitative analysis

As outlined in Chapter 4 (Section 4.3), a gamma distributed logarithm link function flow model was developed to calculate total basin flow into Princess Charlotte Bay. However, the model appeared to underestimate flows that exceeded 1.5 million Ml (Chapter 4, Figure 4.5). It was hypothesised that if these high flow events were not accurately modelled over the period of the barramundi catch data, an extreme event and consequent non-linear threshold response from the fishery might be missed. To determine the likelihood that this occurred, the time series from 1971 – 1987 used to validate the model was examined again. In those months where the model estimated total basin flow exceeded ~1.1 million Ml, flow was underestimated (Figure 6.4). Using this value (1.1 million Ml) as an indicator of poor model performance, the model predictions of total basin flow for the years of barramundi catch data (1989/90 – 2001/02) were re-examined. This period, however, was drier and there were only two months when the model estimated flow exceeded 1.1 million Ml and when flow was likely to be low (1.4% of predictions). Knowing this limitation, both flow and rainfall data were included in the qualitative analysis of extreme events.

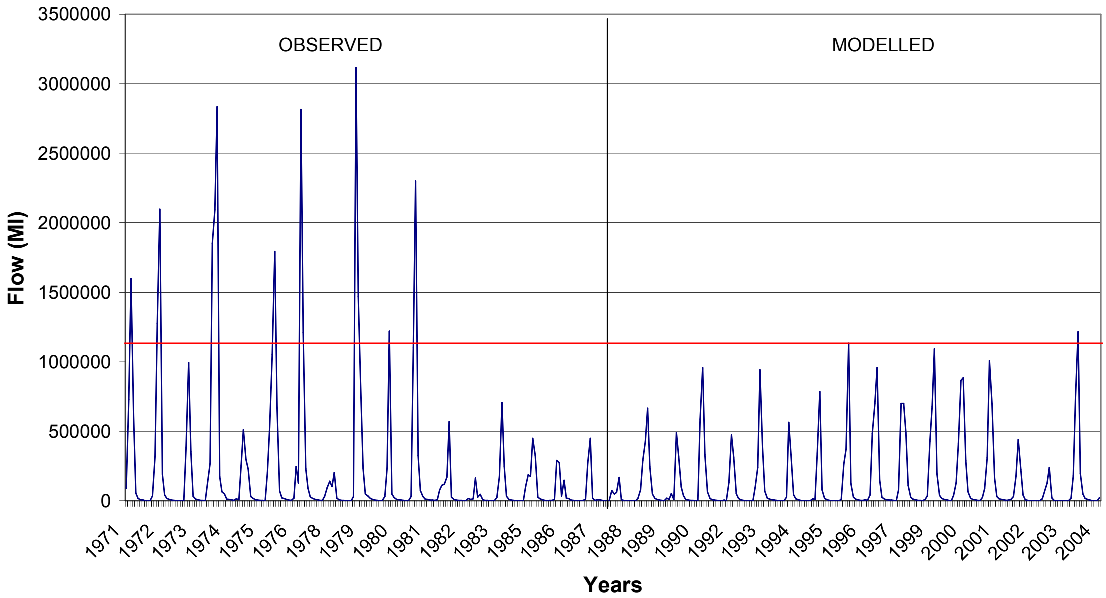


Figure 6.4 Observed (1971 – 1987) and modelled (1988 – 2004) total monthly basin flow for Princess Charlotte Bay. For months where the modelled flow exceeds 1.1 million Ml (red line) values are likely to be an underestimation of total basin flow when compared to observed measures.

In the second stage of the qualitative analysis, a time series of flow and SILO modelled rainfall for Lakefield (1971 – 2006) were plotted for each season (Figure 6.5) and extreme events identified as per the definition.

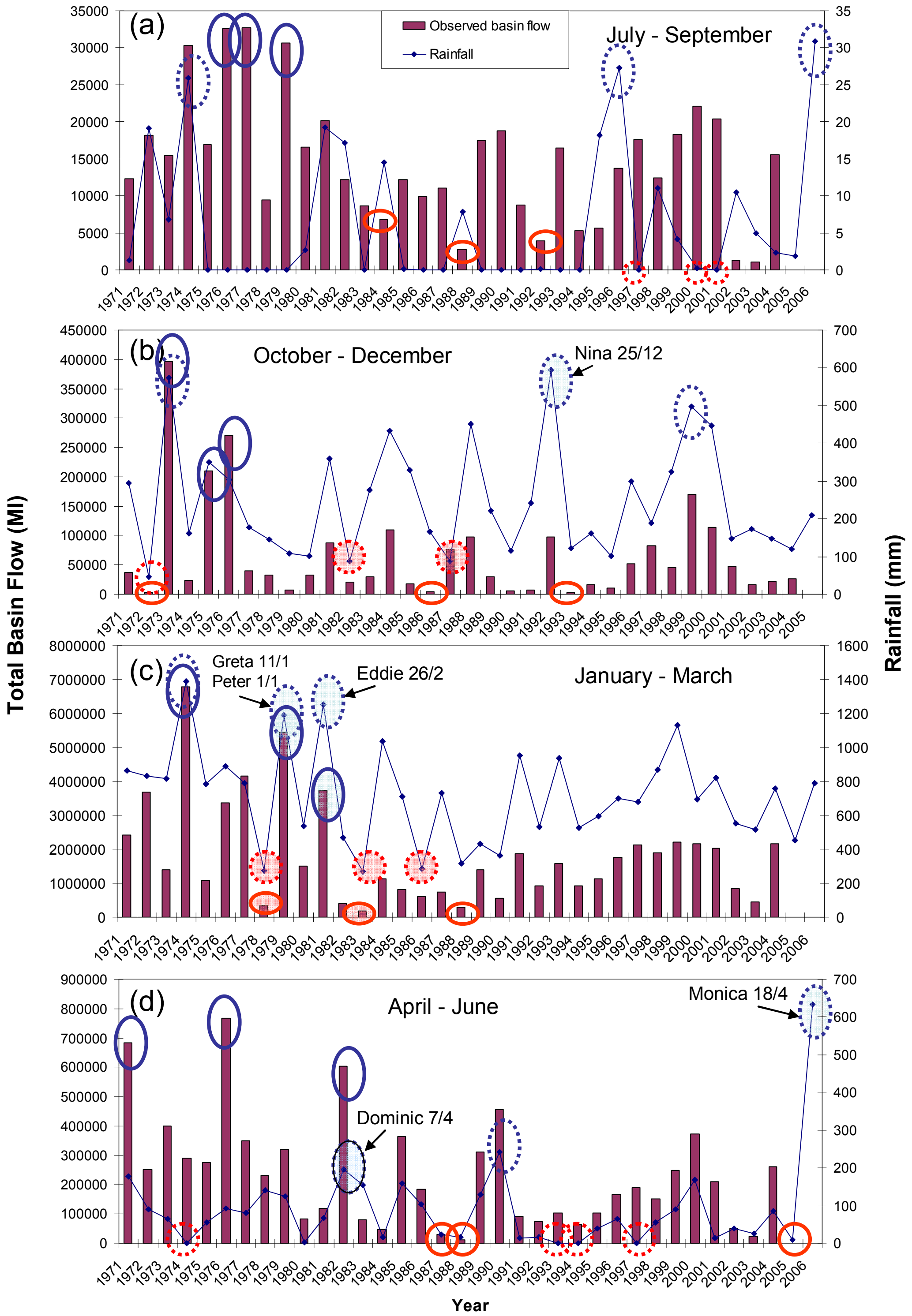


Figure 6.5 Observed and modelled seasonal Princess Charlotte Bay basin flow 1971 – 2006 (bars) and Lakefield seasonal rainfall 1971 – 2006 (line) (a) July – September, (b) October – December, (c) January – March, (d) April – June. Months in the highest and lowest 10% of years (extreme events) are circled for each season (solid blue line for extreme high flow and dashed blue line for extreme high rainfall, solid red line for extreme low flow and dashed red line for extreme low rainfall). Events that correspond with a recorded tropical cyclone or drought are shaded, and in the case of cyclones the event is labelled.

Extreme events identified in the data were then compared with the BOM tropical cyclone data base (http://australiansevereweather.simplenet.com/), which was verified for the Princess Charlotte Bay area with observation notes recorded in the QDNRW stream gauge database, and droughts as identified using Australian Rainman (Clewett, Clarkson *et al.* 2003) (Table 6.2). Twenty-one tropical cyclones are recorded to have affected Princess Charlotte Bay for the years 1970 – 2006 (Table 6.3). A drought was defined as a dry event starting between September and February that had recorded rainfall in the lowest 10% of years. An extreme rainfall event did not always correspond with an extreme flow event, although they did coincide on five occasions. Five of the extreme wet rainfall events and three of the extreme flow events coincided with one or more of the tropical cyclones recorded in the region over the 30 year record examined. Seven of the extreme dry rainfall and flow events coincided with a drought.

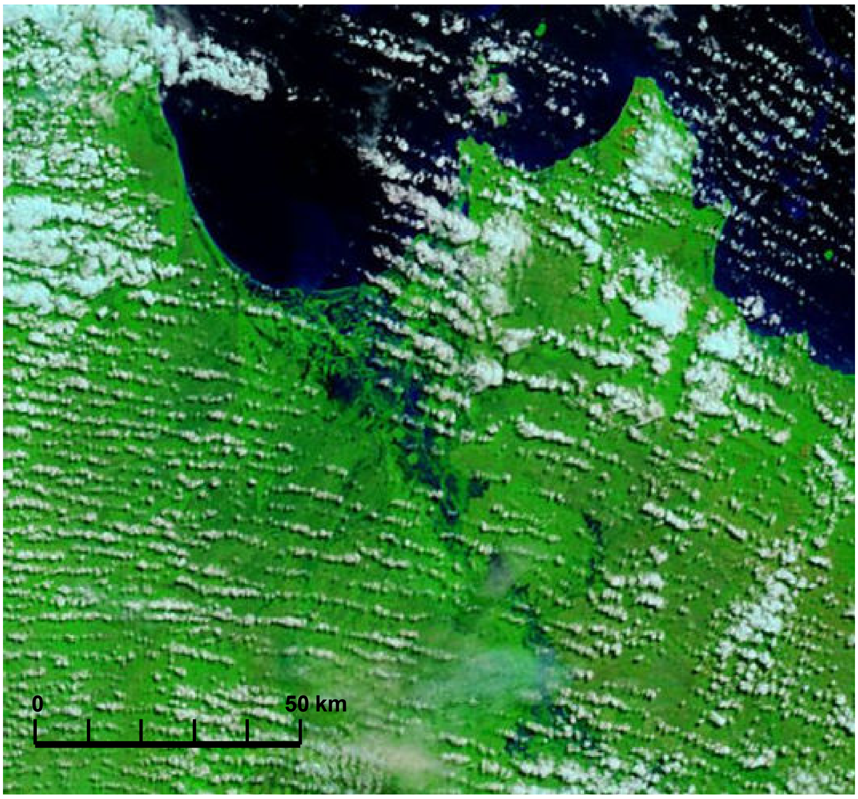
Table 6.2 Droughts affecting the Princess Charlotte Bay area (1970 – 2006) for 120 years of rainfall data at Lakefield. Drought = driest 10% of years in the record. Severe drought = driest 5% of years (Australian Rainman).

Period	Total rainfall (mm)	Duration (months)	% of time in severe drought
September 1972 to February 1973	394	6	100
October 1977 to August 1978	732	11	17
September 1982 to May 1983	804	9	25
October 1985 to August 1986	784	11	0
October 1987 to September 1988	641	12	29
September 1989 to June 1990	909	10	20

A qualitative measure of the impact of an extreme event on the barramundi habitat in Princess Charlotte Bay was possible by downloading images from the NASA MODIS satellite rapid response system (http://rapidfire.sci.gsfc.nasa.gov/subsets/). The 7-2-1 composite was selected as it corresponds to the red, green and blue spectral bands respectively and so has the capacity to distinguish between floods and bare soil. In the images, water appears black, sediments in water dark blue and cloud pale blue. Even a small amount of vegetation will appear green while bare soil is a pinkish brown. Fortuitously, an extreme wet rainfall event occurred in the wake of tropical cyclone Monica (April 2006), while the same week the year before was preceded by a drought (Plate 6.1). As can be seen from the images, the extent of wetland inundation in the 2006 image is extensive and most obvious adjacent to the Normanby River and along the coastal strip. In dramatic comparison, the same week in 2005, which followed an extreme dry period, showed no evidence of wetland inundation. In fact, some areas were obviously dry and bare of vegetation.

Table 6.3 Tropical cyclones affecting the Princess Charlotte Bay (PCB) area (1970 – 2006). The date of the cyclone refers to the day of landfall or major impact (BOM severe weather data set). GOC = Gulf of Carpentaria.

Cyclone	Date	Area	Min hPa	Impacts to the PCB area
Dawn	11/2/70	Weipa	-	Minor vegetation damage, telephone lines down
Faith	13/4/72	Weipa	-	Gales and tree damage at Aurukun
Madge	4/3/73	Cooktown	-	Flooding and roads cut
Hal	7/4/78	Aurukun	-	No damage reported.
Peter	1-2/1/79	GOC	-	Record rainfall and flooding Tully to Cooktown
Greta	11/1/79	PCB	-	Flood rains over northern Cape York
Stan	14/4/79	Weipa	-	High rainfall, no damage or significant flooding
Eddie	10/2/81	PCB	980	Minor impact, minor flooding
Freda	26/2/81	Cooktown	962	Moved away from the coast.
Dominic	7/4/82	Cape Keerweer	950	Damage to buildings and power lines at Edward River Mission
Kathy	19/3/84	Pascoe River	920	Slight tree damage
Rebecca	22/2/85	Weipa	994	Tree damage at Weipa
Tanya	4/4/85	PCB	982	No damage recorded
Ivor	19/3/90	PCB	965	Some structural damage. Tornado damage south of Coen, heavy rains.
Mark	10/1/92	Weipa	980	Widespread minor damage
Nina	25/12/92	Cape Keerweer	960	Structural damage at Aurukun. Archer River reported severe flooding
Ethel	12/3/96	Cape York	980	Vessels in PCB sustained winds of 50 – 60 knots
Les	23 /1/98	GOC	976	Gusts in the Gulf of Carpentaria
Fritz	10/2/04	PCB	920	Gusts to 45 knots
Ingrid	10/2/05	Lockhart River	924	Trees defoliated and felled, 2.7 m storm surge for 60 km along the coast south of landfall
Monica	18/4/06	Peninsula	970	Tree damage and flooding



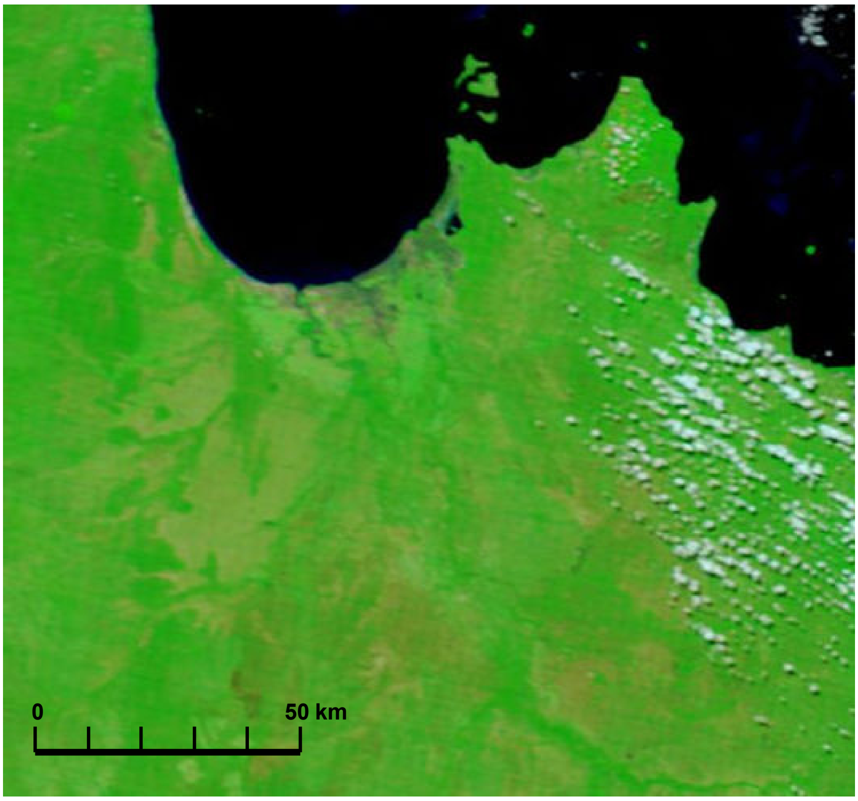


Plate 6.1 MODIS satellite 750 images of Princess Charlotte Bay (top) for an extreme wet event in the wake of cyclone Monica (25 April 2006) and (bottom), an extreme dry event at the end of a drought (19 April 2005). Green indicates vegetation, black exposed water, dark blue sediment in water and pale blue/white cloud (NASA MODIS rapid response system website, November 2006).

6.6 DISCUSSION

To date, research that has examined the impact of climate on inshore fin-fisheries has not included an analysis of non-linear relationships and is instead limited to linear correlation and regression analysis. However, the identification of non-linear responses in a fishery as a result of threshold or extreme climate events will be critical to understand as anthropogenic climate change is likely to increase the frequency of these events. Unfortunately, in most cases a short time-series of fish catch data limits the capacity to quantitatively analyse such responses – a problem in this study too. Nonetheless, the quantitative analysis of the impacts of threshold climate events on barramundi CAE for the Princess Charlotte Bay area found three non-linear variables: pre-wet season rainfall, early dry season freshwater flow and annual evaporation – each two years prior to catch.

In the case of both pre-wet season rainfall and early dry season freshwater flow, linear correlations were not significant and so by traditional methods of analysis these variables would not have been considered further. However, the significant quadratic relationships for both variables with barramundi CAE pinpoint a critical climate threshold. For the years of data, when pre-wet season rainfall reached about 325 mm, the previous positive correlation with CAE was reversed, and the relationship between rainfall and catch turned negative. This indicates that rainfall up to the threshold increased year-class success, however, beyond the threshold cohort success declined. The pre-wet season period two years prior to catch is when nursery habitats are established, mature males are flushed into the estuary and early spawning occurs. An extreme rainfall event at this time of the year has either affected the survival of young-of-the-year fish already in the nursery habitat or reduced the salinity of inshore spawning areas to a level where egg survival is reduced. Pre-wet season freshwater flow did not show either a linear or non-linear relationship with CAE, and so it can be assumed that the response is due to local area rainfall and wetland inundation rather than a destructive flood event that killed fish. For eggs to survive the salinity must be above 10 ppt (Moore 1982) and for larvae it must be above 30 ppt (Davis 1985). Although measurements of water salinity in the mouth of creeks where spawning occurs have not been made for Princess Charlotte Bay at this time of year, it is possible that levels are in some years low enough to affect the survival of these early life cycle stages. Alternatively, water depth may change some aspect of the wetland habitat, and reduce its suitability for the species at this age (e.g. increased predation in deeper water). Regardless of the mechanism, it is clear that there is an optimal amount of rainfall for maximum survival of the young-of-year barramundi.

The quadratic relationship between barramundi CAE and early dry season flow two years prior to catch defines a peak in catch in response to a flow of about 250 000 Ml. Levels of flow below this exhibit the positive correlation between flow and CAE seen in the dry, pre-wet and wet seasons. However, for flows higher than 250 000 Ml in the early dry season, there was a negative correlation with barramundi CAE. During this period juveniles move out of the nursery habitats, which are starting to dry out, and migrate into coastal creeks and upstream to the freshwater reaches of permanent rivers (Russell and Garrett 1985). It is possible that at this stage individuals are susceptible to either an extreme flow event that might cause injury (Neil Gribble, Fisheries Research Scientist, QDPI&F, pers. comm. December 2006), or they are washed out into the estuary where they may be predated upon. Again, the result demonstrates that there is an optimal level of flow – too low or too high and survival is reduced.

The third climate variable that showed an improved correlation with barramundi CAE when fitted with a curve was annual evaporation. In this case, most of the improvement in fit above the linear correlation was due to just one point in the data (2001/02 financial year). In addition, there does not appear to be any physical reason as to why lower evaporation would result in a lower catch. The threshold of about 2 000 mm as defined by the curve is, then, perhaps not as accurate a measure of the evaporation threshold as 2 150 mm, after which every record of CAE was below average (1989/90, 1991/92, 1993/94 – 1997/98). For these years, the water balance (annual rainfall minus annual evaporation) was in all but one case a deficit of more than 1 000 mm. This result suggests that once the evaporative demand exceeds the average depth of the freshwater wetlands in Princess Charlotte Bay (1 m), the nursery habitats are significantly reduced as is survival of fingerlings and subsequent catch.

In summary, when compared to the proposed hypothesis (Table 6.1), the non-linear relationships between CAE and both freshwater flow and evaporation were predicted correctly. The reduction in catch in response to high rainfall in the pre-wet season was not predicted, although, the drop in subsequent catch in response to low rainfall was. Neither terrestrial nor sea surface temperatures returned a non-linear relationship with barramundi CAE, although, it could be that the threshold for each of these variables was not seen over the period of available data. This is not an unlikely assumption as Princess Charlotte Bay lies near the middle of the species latitudinal and temperature range.

With each of these quantitative analyses it is worth noting that complexities in the climate system means that the use of modelled climate data will not necessarily describe the full range of events accurately (e.g. Kumar, Hoerling *et al.* 2005). Additionally, as there are so few points in the time series, the removal of a single year may alter the threshold values identified. For this reason, the ongoing inclusion of future data would be advisable in order to confirm these results. Future analyses at shorter time scales (e.g. monthly or weekly) might also reveal other thresholds depending on the extent and timing of the event. Finally, the thresholds identified in this analysis will not necessarily be transferable to other barramundi fisheries along the north-east coast due to differences in the spatial and temporal aspects of other areas. Each of these limitations needs to be taken into consideration when quantitatively analysing the impacts of extreme events on a fishery.

The qualitative comparison of extreme wet and dry events identified only sporadic alignment with either a drought or tropical cyclone respectively. For this reason, the actual measure of a climate variable is the better descriptor of what is happening in the fishery than records of droughts or cyclones. The qualitative analysis of changes in habitat, however, returned more promising results. Researchers in the Northern Territory conclude from their work that including a measure of inundated wetland nursery habitat would significantly improve the model estimates of barramundi catch in subsequent years (Griffin and Kelly 2001). However, due to the nature of the landscape during the wet season, quantifying such measure is a difficult, timely and costly task at ground level and so to date has not been undertaken regularly. In this study, the use of MODIS satellite imagery demonstrates a viable alternative that combined with GIS technology has the potential to provide a quick and cost effective option for quantifying wetland habitat over extensive areas. In the example provided, images of Princess Charlotte Bay show clearly the difference between inundated areas and bare, or vegetated ground in the wake of an extreme wet and extreme dry event, respectively.

Certainly, on-ground validation of the images would need to be undertaken to ensure that there is a clear differentiation between substrates (e.g. dense reed beds and grasslands), and the relationship with catch would need to be quantified if the technique was to be used to model future harvest. However, higher resolution images to those demonstrated here are available and may provide a more accurate measure. One obvious limitation of the technique is cloud cover, which in the example provided blocks a large proportion of the image taken in the wake of tropical cyclone Monica. Another is the historical limit of satellite images, which, depending on the satellite, are only available in a regular sequence for the past five to ten years.

6.7 CONCLUSION

The effects of an extreme or threshold climatic event on the catch of Princess Charlotte Bay barramundi were examined using both qualitative and quantitative analysis. Pre-wet season rainfall, early dry season freshwater flow and evaporation all had a significant quadratic relationship with barramundi CAE two years later. For pre-wet season rainfall, CAE peaked at about 325 mm and declined thereafter, representing a possible decrease in salinity and reduced survival of eggs at spawning, or increased predation of fingerlings in the wetland habitat due to higher water levels. A peak in CAE also occurred in response to approximately 250 000 Ml of early dry season flow, beyond which fingerlings migrating into rivers were perhaps injured or flushed into the estuary and predated upon. The quadratic curve of evaporation versus CAE peaked at about 2 000 mm although the most dramatic declines in CAE occurred when evaporation exceeded 2 150 mm. A water balance calculation estimated that this level of evaporative demand would exceed the average depth of the freshwater wetlands in Princess Charlotte Bay. The result would suggest that both nursery habitats and young-of-year survival was reduced in years when the 2 150 mm evaporation threshold was exceeded. A qualitative analysis of long-term climate data indicated that extreme events are only occasionally associated with either a cyclone or drought. MODIS satellite images of the study area after both an extreme wet and extreme dry event showed significant and dramatic differences in the area of inundated wetlands and hence nursery habitat. The analysis of extreme events and identification of species climate thresholds is likely to become increasingly important in the face of anthropogenic climate change if these events increase in frequency as expected.

CHAPTER 7: LONG-TERM CLIMATE EFFECTS: NORTH-EAST QUEENSLAND

7.1 INTRODUCTION

Long-term (inter-annual) climate variability, as generated by large-scale climate cycles such as the Interdecadal Pacific Oscillation (IPO), has been shown to have large-scale impacts on some of the pelagic fisheries of the world including the Norwegian and Icelandic herring, Norwegian cod and Peruvian anchovy (e.g. Klyashtorin 1998). Linking variations in long-term climate variations with fluctuations in fisheries catch provides an opportunity for forecasting catch and managing species a number of years in advance (Klyashtorin 2001). However, apart from a few studies linking salmon catch (an anadromous species) with long-term climate variables in the northern hemisphere (e.g. Beamish and Bouillon 1993; Mantua, Hare *et al.* 1997), the analysis of long-term climate impacts on inshore fisheries is limited. As reviewed in Chapter 2, only three studies have examined the possible effects of long-term climate variations on Australian fin-fish. All of these studies consider marine species and the impact of changes in zonal westerly winds driven by the Latitude of the Subtropical Ridge (LSTR). The first examines jack mackerel (*Trachurus declivis*), southern blue-fin tuna (*Thunnus maccoyii*) and barracouta (*Thyrsites atum*) (Harris, Griffiths *et al.* 1992) in Tasmania. The second, gemfish (*Rexea solandri*) (Thresher 1994) again in Tasmania, and the third, King George whiting (*Sillaginodes punctata*) off the coast of Victoria (Jenkins 2005). There are no studies that examine the impacts of long-term climate variations on estuarine fin-fish. An analysis of barramundi catch data in the Fitzroy River region of central Queensland noted a 15 – 20 year cycle that the authors propose was driven by summer rainfall and flow three to four years earlier (Robins, Halliday *et al.* 2005). However, the spatial extent of this oscillation in catch, or possible connections with long-term climate cycles, was not explored. Knowing if long-term, large-scale climate patterns were driving these cycles in catch may provide the capacity to extend temporally and spatially the forecast of catch depending on the species. This chapter addresses research question 6: Do long-term, large-scale climate oscillations impact on barramundi catch?

7.2 STUDY AREA

North-east Queensland as defined in this section of the study spans over eight degrees of latitude from Port Douglas in the north, to Bundaberg in the south (Figure 7.1). The region is diverse in topography, geology, vegetation and land use, and contains an abundance of endemic and in some cases rare or endangered species and ecosystems. The economy is based on agriculture, tourism, mining, fishing and manufacture (Crimp, Balston *et al.* 2003). The cities of Cairns, Townsville, Mackay, Rockhampton and Bundaberg are major population centres.

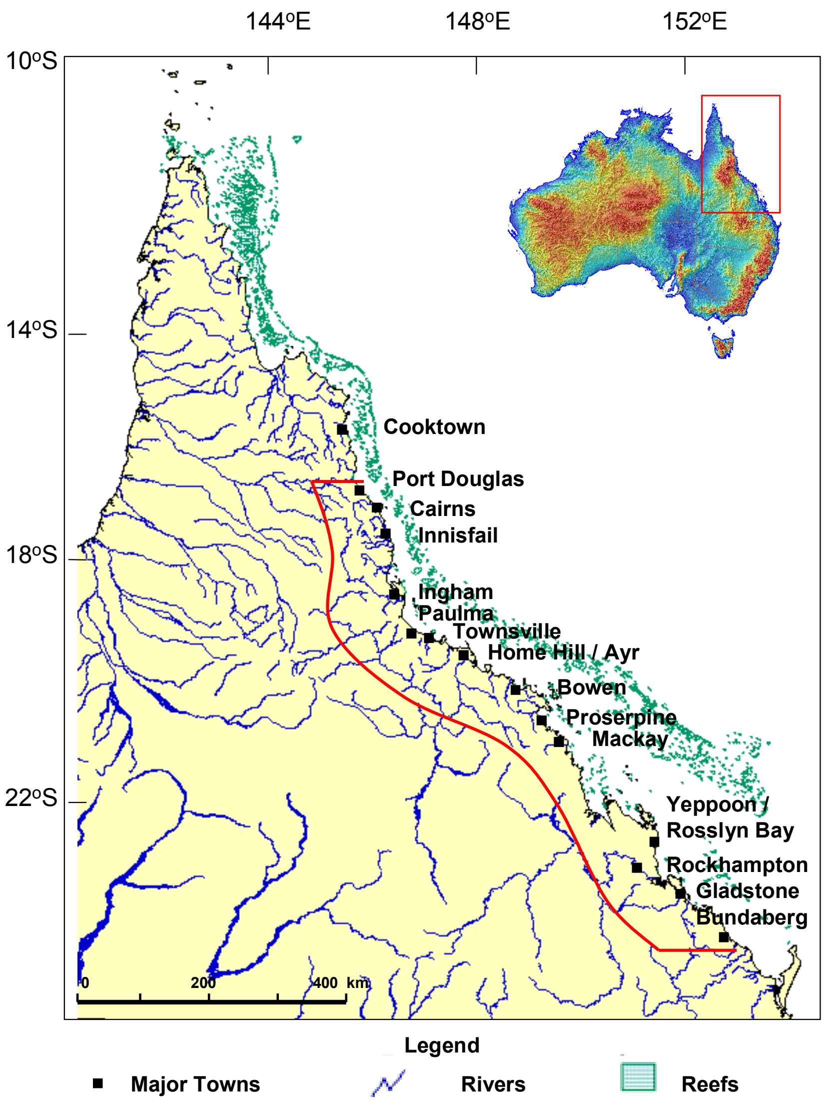


Figure 7.1 North-east Queensland study area. The centres that have Fish Board data used in the analysis are shown (adapted from the Queensland Fisheries Service. CHRIS website, October 2006). The study area includes coastal and inshore areas to the east of the red line.

Topography

The study area follows the east coast of Queensland between the Great Dividing Range and the Coral Sea. Much of the far north-east coast from Port Douglas south to Townsville is defined by steep, forested mountains and includes Queensland's three highest mountains, which rise to over 1500 m (DPI 1995b). The highlands consist of granitic bedrock and lower slopes comprise red to red-brown loam earths (Olsen 1983). Soils of the coastal plains of the Cairns region (as far north as the Daintree River north of Port Douglas and south to Ingham) comprise ferrosals, red earths, red podsolic and sodosols, some areas of siliceous sand near Cardwell, and krasnozems around Innisfail (DPI 1995a; DPI 1995b; Olsen 1983). The Townsville region south to Bundaberg is flatter in topography as the ranges are lower in altitude and further from the coast. Soils are commonly granitic or sandstone, with yellow, brown and red duplexes, sand, silt, clay and alluvial overlays. The area from Mackay south to Broad Sound and around Bundaberg consists of acid volcanic soils.

River systems

Due to the proximity of the coastal ranges to the coast, rivers flowing east in the Cairns, Innisfail and Hinchinbrook regions tend to be short and straight with small catchments or tidal creeks and many minor waterways. Total catchment area is 49 520 km^2 and average annual runoff 24 600 000 Ml (DPI 1993). Further south as the landscape flattens out, the catchments increase in size and rivers flow more slowly. The Burdekin and Fitzroy Rivers each have extensive catchments (133 510 km^2 and 142 645 km^2 respectively), dominated by grazing systems and some cropping (DPI 1993). Total average annual flow from the two rivers is 17 950 000 Ml, over a third of the total runoff for the entire study area. Other rivers along the coast between Townsville and Bundaberg are not as large and include the Don near Bowen (700 000 Ml), the Proserpine near Mackay (1 400 000 Ml), and streams of the Pioneer – O'Connell and Shoalwater Bay – Sarina areas north of Rockhampton (total outflow 8 450 000 Ml) (DPI 1993). All rivers in the study area are affected by the strong seasonality of the tropical climate system, which impacts on air temperature, salinity, water quality and sediment load. Freshwater flow in the Barron River near Cairns during La Niña years is 188% that during El Niño years (Lough 1998). Sediment levels range from 7000 $mg.l^{-1}$ during peak flow events down to 10 $mg.l^{-1}$ during the dry months, and tropical cyclonic flood plumes extend up to 60 km off the coast (Wachenfeld, Oliver *et al.* 1998).

Land use

A number of the rivers and streams across the study area have been impounded for the generation of hydro-electricity, irrigation and urban needs and/or have been modified in other ways. Changes include the draining of wetlands for sugar cane and urban expansion, clearing of trees and riparian areas for grazing and agriculture, introduction of fingerlings and selective catch of fish by recreational fishers, deterioration of water quality due to agricultural and urban runoff, sediment, fertilizer and chemical inputs or boating activities (DPI 1995b; Heap, Bryce *et al.* 2001). In some cases these modifications are extensive, and have affected fresh water flows, wetlands and estuarine fisheries habitats. Fisheries between Townsville and Cairns in particular have seen a dramatic decline in barramundi catch in recent years due to a combination of the above – a trend that is likely to continue (Midgley 1987).

Climate

Rainfall gradients are steep along the coast, especially in the far north-east region, because of the topographic effect of the coastal ranges. Average annual rainfall across the north of the area ranges from 2 132 mm at Cairns down to only 910 mm at Mareeba (Clewett, Clarkson *et al.* 1994) thirty-seven kilometres inland (Figure 7.2). Average annual rainfall at Bundaberg in the south of the study area is 1 105 mm. Most of the year the south-east trade winds dominate, replaced in the summer months in the north of the study area by the north-west monsoon winds (Downey 1983). Cloudiness is at a maximum in the summer months during the monsoon (average 5 oktas) and lowest in the winter dry season (Downey 1983). Tropical cyclones affect the region regularly causing damage to the reef and foreshore areas through storm surges, extreme wind and wave forces, flooding and associated sediment, nutrient and pollution loads. In the years 1970 – 1998 a total of 138 cyclones affected Queensland waters impacting on most areas adjacent to the Great Barrier Reef at least once (Puotinen, Done *et al.* 1997).

Air temperatures range from a mean maximum of 32°C in Cairns during the summer months to a mean minimum of 9°C at Rockhampton over winter (BOM 1988) (Figure 7.3). Sea surface temperatures range from 21°C – 29°C and vary seasonally by 6°C – 8°C (Downey 1983). Temperatures inside the Great Barrier Reef Lagoon range from about 23°C in July – August to 28°C in January – February. Inshore areas generally exhibit a greater seasonal range than offshore areas - from 21°C to 30°C (Wachenfeld, Oliver *et al.* 1998).

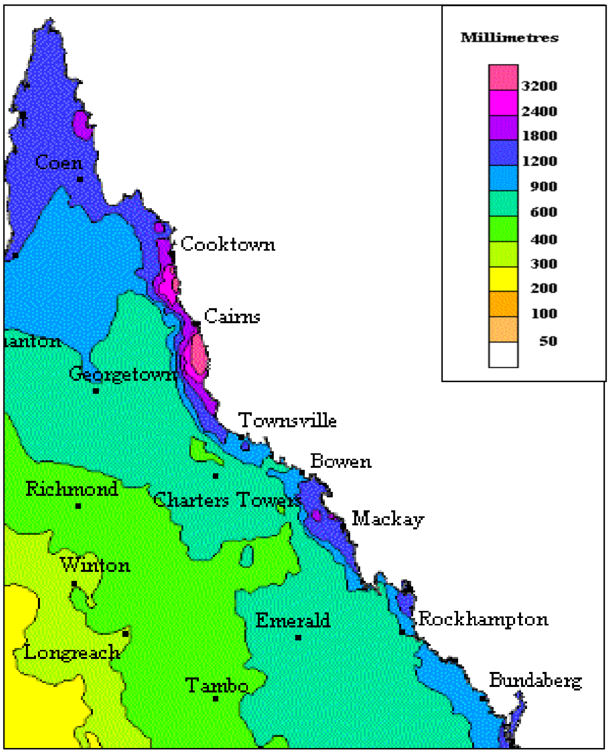


Figure 7.2 Average annual rainfall for north-east Queensland 1961 – 1990 (BOM 2005).

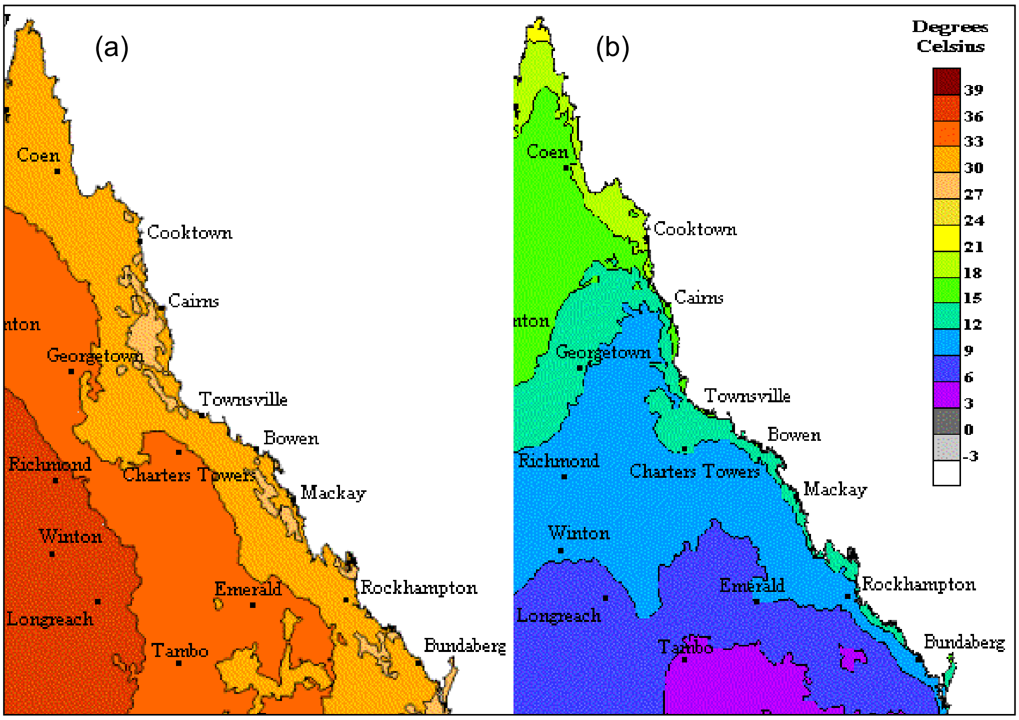


Figure 7.3 Average (a) maximum and (b) minimum air temperature for north-east Queensland 1961 – 1990 (BOM 2005).

7.3 DATA

Data collated for the long-term analyses were fisheries catch data as recorded by each Fish Board along the coast, and indices of the Interdecadal Pacific Oscillation (IPO), the Southern Annular Mode (SAM), the Quasi Biennial Oscillation (QBO) and the latitude of the sub-tropical ridge (L-index). Issues of data quality and limitations where they exist are highlighted for each variable, and the collation and preparation of data prior to analysis is described.

Fisheries data

Fish Board data from 1945 to 1972 is a record of the total weight of fish landed in each financial year (1 July – 30 June) for depots along the Queensland coast. There is no measure of effort. Changes that may have impacted on fisheries catch over the years are also not recorded and include amendments to catch regulations, habitat degradation (including the draining of wetlands for sugar cane and urban expansion), or changes to access (introduction of green zones, marine national parks and fisheries habitat areas). Data were recorded at the following depots in north-east Queensland: Port Douglas (the most northerly outpost), Cairns, Innisfail, Ingham, Townsville, Home Hill, Ayr, Paluma, Bowen, Proserpine, Mackay, Yeppoon, Rosslyn Bay, Rockhampton, Gladstone and Bundaberg (Q.F.B 1937; Q.F.B 1941; Q.F.B 1942; Q.F.B 1943; Q.F.B 1947; Q.F.B 1948; Q.F.B 1949; Q.F.B 1950; Q.F.B 1955; Q.F.B 1956; Q.F.B 1957; Q.F.B 1959; Q.F.B 1962; Q.F.B 1963; Q.F.B 1964; Q.F.B 1966; Q.F.B 1973) (Table 7.1). Total financial year barramundi landings (kilograms) for all depots in north-east Queensland from Port Douglas in the north, to Bundaberg in the south, were extracted from a Microsoft Access® 2000 database containing data from each Fish Board (as recorded by depots in their annual reports of the North Queensland Fish Board and Queensland Fish Board). Original figures included both metric and imperial measurements and entries of fillets as well as gilled and gutted fish weights. Measures of catch were standardised into kilograms of gilled and gutted whole fish and entries thoroughly checked for keystroke and other data errors (Robins, Halliday *et al.* 2005). Early Fish Board landings (1940s – 1950s) would have represented locally caught fish only, as operations were unsophisticated, without refrigeration, and mostly one-person owner operators living locally (Haysom 2001; Hundloe 1985; Quinn and Garrett 1992). Additionally, there was only limited opportunity for transport of barramundi caught in areas distant from the depots and local demand for barramundi was not high. Because of this, these early Fish Board records were a reasonably good estimate of catch in each area. However, in the mid 1960s the extensive Gulf of Carpentaria (GOC) barramundi fishery was opened up (Munro 1988) and, once the road south from Cairns was sealed and dry refrigeration came into use in the 1970s, the range for cold transport was extended and fishermen working further a field had a means of transporting their catch to Cairns in the north and other depots further south (Bob O'Halloran, Fleet Master, Sea Swift, pers. comm. August 2005). By the late 1970s, there was an increasing number of black-market sales from the back of boats to restaurants and smaller outlets which were virtually impossible to quantify (Gray and Spencer 1986). In addition, the Fish Board's powers only related to fish harvested and sold in Queensland, it had no control over fish sold interstate or overseas (Gray and Spencer 1986). Later Fish Board records of landings, then, do not include landings processed by independent or private companies, recreational catch, fish sent to interstate or international export markets, or black market sales – all of which are believed to represent a significant proportion of total catch for these years (Gray and Spencer 1986; Russell 1988).

Table 7.1 Fish Board data for north-east Queensland (Queensland Fish Board 1937 – 1981).

Depot	Region	First year of records	Final year of records
Port Douglas	Cairns	1979 / 1980	1980 / 1981
Cairns	Cairns	1948 / 1949	1980 / 1981
Innisfail	Cairns	1946 / 1947	1980 / 1981
Ingham	Townsville	1955 / 1956	1961 / 1962
Townsville	Townsville	1945 / 1946	1980 / 1981
Home Hill	Townsville	1958 / 1959	1975 / 1976
Ayr	Townsville	1945 / 1946	1965 / 1966
Bowen	Townsville	1956 / 1957	1980 / 1981
Paluma	Townsville	1980 / 1981	1980 / 1981
Proserpine	Mackay	1957 / 1958	1966 / 1967
Mackay	Mackay	1945 / 1946	1980 / 1981
Yeppoon	Fitzroy	1948 / 1949	1980 / 1981
Rosslyn Bay	Fitzroy	1975 / 1976	1980 / 1981
Rockhampton	Fitzroy	1945 / 1946	1980 / 1981
Gladstone	Fitzroy	1945 / 1946	1980 / 1981
Bundaberg	Burnett	1945 / 1946	1980 / 1981

After about 1970, records from the Cairns region (Port Douglas, Cairns, Innisfail and Ingham Fish Boards) include landings from far northern centres (including Princess Charlotte Bay and Karumba in the Gulf of Carpentaria) (Figure 7.4). For this reason, data from 1970/71 onwards as recorded by the Cairns region depots were excluded from the analyses to ensure fish caught outside the study area were not counted (Figure 7.5).

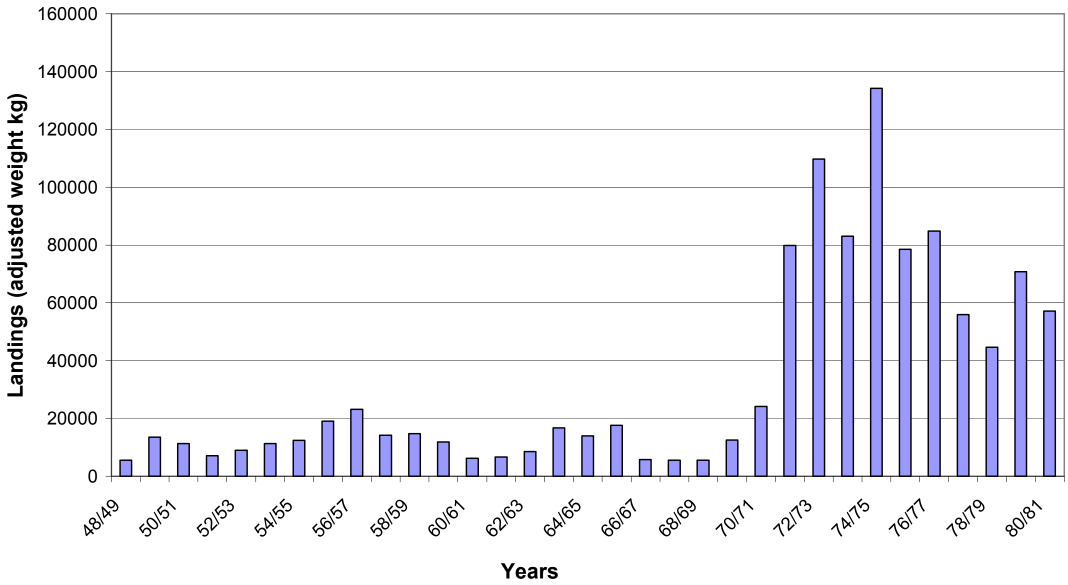


Figure 7.4 Annual financial year (1 July – 30 June) Fish Board barramundi landings for the Cairns region (Port Douglas, Cairns, Innisfail and Ingham Fish Boards) for the years 1948/49 – 1980/81. Landings after about 1970 include fish catch in regions further a field such as Princess Charlotte Bay and the Gulf of Carpentaria and so data from these years for this region were not included in the analyses.

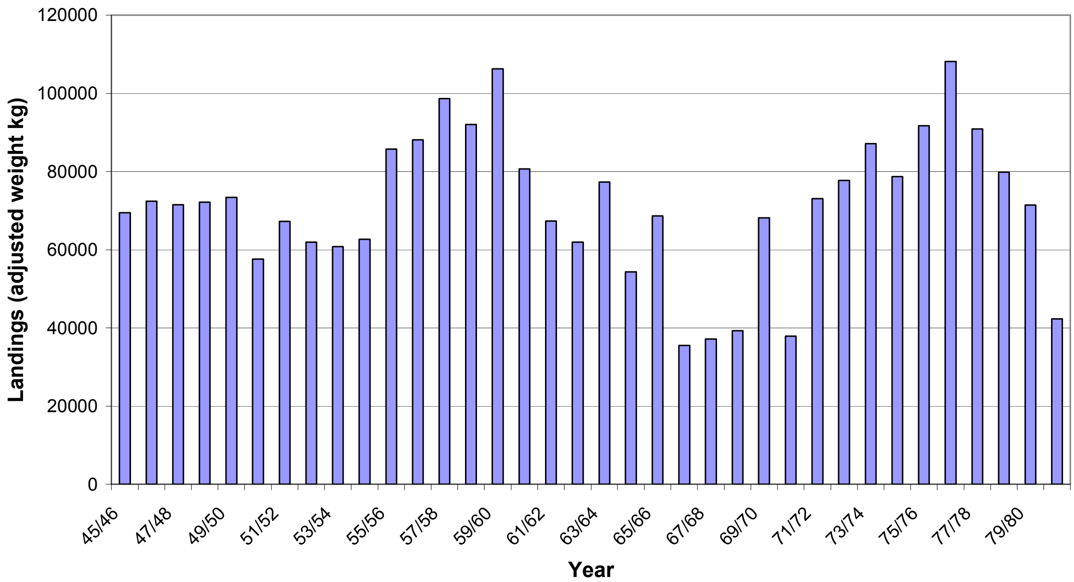


Figure 7.5 Total annual financial year (1 July – 30 June) Fish Board barramundi landings for north-east Queensland (1945/46 – 1980/81). Data includes landings from Port Douglas in the north of the study area to Bundaberg in the south, but excludes data from the Cairns region (Port Douglas, Cairns, Innisfail and Ingham Fish Boards) for the years 1970/71 – 1980/81 to ensure only fish caught in the study area were included in the analyses.

Climate data

This section introduces the mechanisms of large-scale climate oscillations and explains the climate indices used in the long-term analyses.

<u>The Interdecadal Pacific Oscillation (IPO)</u>

The IPO has been shown in a number of studies to correlate significantly with decadal rainfall anomalies across Australia (Folland, Parker *et al.* 1998; Latif, Kleeman *et al.* 1997; Power, Tseitkin *et al.* 1999) and as described in section 2.1 may modulate ENSO at the shorter timescale. Other studies conclude that, although the effect from the IPO is most significant in the summer months (January – March), the oscillation is not significantly correlated with rainfall in the north-east of the country (Meinke, deVoil *et al.* 2005), instead showing stronger relationship with rainfall in the south-east of the continent. No modulating effect or signal from the IPO was detected in either flood frequency north of the Tropic of Capricorn (Micevski, Franks *et al.* 2006), or June – November rainfall across the coastal sugar regions (Jones and Everingham 2005). There is, however, some evidence to suggest that the IPO influences the formation of tropical cyclones in north-east Australia, as more tropical cyclones form in the region during positive phases of the IPO when vertical wind shear is reduced (Grant and Walsh 2001).

A number of indices of the IPO have been calculated using empirical orthogonal function analysis of either SSTs or air temperature (e.g. Folland, Parker *et al.* 1998; Zhang, Wallace *et al.* 1997). Power, Tseitkin *et al.* (1999) concluded that all were very similar with the same component of variability on the inter-decadal time scale common to each. This study used the monthly IPO index calculated by Folland, Parker *et.al.* (1998), which is based on the Hadley Centre SST and GISST3 data sets (1856 – 2001). The variable used for analyses was the average IPO index for the period November 1 – April 30 to capture any influence on cyclone activity.

<u>The Quasi-Biennial Oscillation (QBO)</u>

The Quasi-biennial Oscillation (QBO) is reviewed in detail by Baldwin, Gray *et al.* (2001) but can be described in brief as a near-biannual (27 – 28 month) oscillation between predominantly easterly and westerly directions of the equatorial stratospheric winds (McGregor and Nieuwolt 1998). The maximum amplitude of both east and west phases occur near 20 hPa, although, period and amplitude vary considerably from cycle to cycle (Naujokat 1986). The effect of the QBO on tropical climate systems is still unclear, as it appears to be independent of ENSO and has more impact on higher latitudes (McGregor and Nieuwolt 1998). However, Gray and Scheaffer (1991) reported that, like the IPO, the QBO has an impact on tropical cyclone development. The frequency of intense cyclones in the western Pacific (particularly in the Australian region), is reduced during easterly phases of the QBO due to an increase in upper tropospheric / lower stratospheric wind shear – a regime that inhibits cyclone development.

Tropical stratospheric winds have been measured since 1957 as part of the global radiosonde network. The QBO data set used in this analysis was extracted from the Berlin Stratospheric Data Series produced by combining the observations at three radiosonde stations: Canton Island, Maldive Island and Singapore (http://dss.ucar.edu/cdroms/karin_labitzke_strat_grids/html/section5.html). The index is a measure of mean monthly zonal U-wind components from 1953 – 2002 at the 20 hPa level (the altitude where the maximum amplitudes of both easterly and westerly phases typically occur) and is considered representative of the equatorial belt, although, uncertainties exist in the early years due to a scarcity of observations. The variable used in the analyses was an average QBO index for the period November 1 – April 30, again to capture any effects on tropical cyclone incidence. Negative values of the QBO represent the easterly phase (zonal winds from the east) when cyclone development in the western Pacific is reduced, and positive values the westerly phase (zonal winds from the west).

The Southern Hemisphere Annular Mode (SAM)

A number of oscillations have been defined in relation to fluctuations in atmospheric and oceanic variables in the high latitudes of the Southern Ocean. The atmosphere / ocean coupled Antarctic Circumpolar Wave (ACW) propagates eastwards around the Southern Ocean at an average speed of 45 degrees of longitude per year, taking about eight years to complete the cycle, and exhibits phases of cool and warm sea surface temperature (SST) anomalies linked to equatorward and poleward surface winds respectively (White 2000). Recent research indicates that the ACW is a combination of two signals, one a standing wave with a period of oscillation across the Southern Ocean of around 3.3 years, and the second signal most likely forced remotely by ENSO with a periodicity of around five years (Venegas 2003).

The terms Antarctic Oscillation (AO) and Southern Hemisphere Annular Mode (SAM) refer to the same "large scale alternation of atmospheric mass between the mid-latitude surface pressure and high latitudes surface pressure" (Gong and Wang 1999; Thompson and Lorenz 2004) is now thought to be the dominant mode of interannual climate variability in the Southern Hemisphere (Visbeck and Hall 2004). Effects from the oscillation of the SAM have been shown to extend into the tropics and sub-tropics and include variability in temperature, mean sea level pressure and rainfall across the Australian continent (Gong and Wang 1998; Thompson and Lorenz 2004; Venegas 2003; Visbeck and Hall 2004). Values of the SAM index are positively correlated with mean sea level pressure (MSLP) in the mid-latitudes and negatively correlated with winter rainfall across southern and eastern Australia (Sturman and Tapper 2006). Positive values of the SAM have also been associated with increased summer rainfall across central and eastern parts of the continent (Sturman and Tapper 2006).

For this study, the most recently calculated index for the SAM was extracted from the Joint Institute for the study of the Atmosphere and Ocean website for the years 1948 – 2005 (http://www.jisao.washington.edu/aao/slp/#analyses) derived from the NCEP – NCAR reanalysis data. The index is defined as the leading principal component of 850 hPa geopotential height anomalies south of 20^{o}S (Thompson and Wallace 2000) and is standardised to the 1979 – 2004 period. It was noted that Marshall (2002) raised concerns about the quality of the index prior to 1979 due to changes in the measurement of air pressure. The variable used in the analyses was the financial year average (1 July – 30 June) as a measure of effects on rainfall throughout the year.

Latitude of the Sub-tropical Ridge (LSTR)

The *L*-index is a measure of the latitude of the sub-tropical ridge described in Section 2.3, and has been defined by a number of authors. The index used in this study is a monthly anomaly calculated using the base period 1961 – 1990 as per Das (1956) and Pittock (1973) (Allyson Williams, Climatologist, QDPI&F, pers. comm. March 2006). The *L*-index identifies the latitude at which the highest monthly mean sea level pressure is recorded across nine locations along the Australian eastern seaboard. The stations used in the analysis are: Cairns, Townsville, Rockhampton, Brisbane, Sydney, Moruya, Gabo Island, Launceston and Hobart. Previous research (e.g. Pittock 1971) showed varied relationships between eastern Australian rainfall and the *L*-index depending on season. Negative anomalies of the *L*-index indicate the LSTR is further north than average while positive anomalies indicate the high pressure ridge is further south (Drosdowsky 2005). The average January – March *L* anomaly was used in these analyses as a measure of the variability of rainfall at the time critical to early survival and development of the barramundi. Each variable selected for analysis is shown in Table 7.2.

7.4 METHODS

Analyses followed the process model developed in Chapter 3 (Figure 3.1) and are described in more detail below:

1. A hypothesis was designed to link long-term climate variability and barramundi catch for north-east Queensland;
2. An exploratory analysis of the climate indices and Fish Board barramundi landings, including the generation of time series graphs and scatter plots, was undertaken in order to contextualise the timing of the study against long-term climate data and to identify possible relationships;
3. Variables were tested for normality and transformed prior to further analyses if necessary;
4. A Pearson correlation matrix of climate indices was generated in order to identify possible collinearity;
5. A lag analysis was undertaken between barramundi Fish Board landings and climate indices for up to five years;
6. Relationships between indices significantly correlated with catch were further explored using time series graphs.

Table 7.2 Fisheries and climate data used in the identification of effects from long-term climate oscillations on the commercial barramundi fishery of north-east Australia.

Variable	Source	Format	Notes	Transformations
Barramundi catch	Fish Board records	Financial year landings (1 July - 30 June)	Sum of 16 depots 1945/46 – 1980/81	Untransformed
Interdecadal Pacific Oscillation (IPO)	Folland *et al.* (1998)	Average November - April value	1943/44 – 1980/81	Untransformed
Quasi-Biennial Oscillation (QBO)	Berlin Stratospheric Data Series	Average November - April value	1953/54 – 1980/81	Untransformed
Southern Hemisphere Annular Mode (SAM)	JIAO	Financial year (1 July - 30 June) average	1948/49 – 1980/81	Untransformed
Latitude of the Sub-tropical ridge (*L*-index)	QDPI&F	Average January - March *L* anomaly	1952/53 – 1980/81	Untransformed

QDPI&F = Queensland Department of Primary Industries and Fisheries; JIAO = Joint Institute for the study of the Atmosphere and Ocean.

As with the short-term data, a number of limitations and assumptions were made when undertaking the analyses. The first is that despite the limitations in Fish Board data it is assumed to be a reasonable measure of barramundi catch and population size across the study area for the years considered. Secondly, that the time to development for individual fish from spawning to catch is relatively consistent both temporally and spatially across the study area. Finally, without detailed records of changes to fishing technique, habitat, stream dynamics and other anthropogenic influences, the impact from these factors is assumed to be similar across the region.

Hypotheses

Hypotheses linking long-term climate variability (as measured by indices of the IPO, QBO, SAM and LSTR) and Fish Board barramundi landings were developed (Table 7.3). Predicted relationships were based on the effects from each long-term climate cycle on the climate of north-east Queensland as identified in the literature, and the likely impact on the barramundi fishery at each stage in the development of the fish as determined from the results of Chapters 4 and 6 (Figure 3.2).

As outlined in section 7.3, both the IPO and QBO have been shown to affect tropical cyclone activity in north-east Queensland. Positive phases of the IPO are associated with warmer SSTs in the eastern Pacific Ocean (Folland, Parker *et al.* 1998), decreased vertical wind shear in the western Pacific Ocean and a corresponding increase in cyclone development in the north-east Queensland region (Grant and Walsh 2001). Negative values of the QBO relate to a decrease in intense tropical cyclones in the north-east Queensland region due to an increase in upper tropospheric/lower stratospheric wind sheer. How an increase or decrease in cyclone activity might affect the barramundi fishery is difficult to predict. Increased flow and rainfall would increase habitat areas for fingerlings and juveniles and flush mature males downstream into the commercial fishery in the year of catch (Chapter 4). However, depending on the severity and timing of the event, cyclones may also be destructive and reduce subsequent catch (Chapter 6).

Both the SAM and LSTR have been shown to affect rainfall across the continent. Positive correlations between the SAM and summer rainfall across eastern and southern Australia would suggest that positive values of the SAM are associated with conditions conducive to barramundi survival, particularly in the early life cycle stages. As northerly anomalies of the *L*-index are negative and southerly anomalies of *L* are positive, it would be expected that drier conditions in the north-east region of Australia are coincident with negative *L* values and wetter conditions with positive values. As wetter, warmer conditions have been shown to enhance early life stage survival in the barramundi and increase subsequent catch (see section 2.3), the correlations with the SAM and LSTR would be expected to be positive. As none of the indices considered are noted to affect SSTs in the region, the impact on spawning and larval stages is expected to be minimal.

Table 7.3 Hypothesis linking long-term climate cycles and commercial barramundi catch as recorded by north-east Queensland Fish Board depots. Indices that are expected to correlate with increased population and subsequent catch are indicated by a "+" sign while those that are expected to decrease survival and resulting catch are indicated by a "–" sign. Climate variables that are not linked in the life cycle model to the developmental stage of the fish are marked as not applicable (n/a).

Life cycle stage / Climate index	Spawning	Larvae	Fingerlings	Juveniles	Maturing males	Returning males
IPO	n/a	n/a	-	-	+	+
QBO	n/a	n/a	-	-	+	+
SAM	n/a	n/a	+	+	+	+
L-index	n/a	n/a	+	+	+	+

7.5 RESULTS

Exploratory analysis

To determine the range of climate variability captured during the time of available Fish Board data, a plot of rainfall (the most variable climate parameter) at both Cairns in the north and Bundaberg in the south of the study area was generated and the period of available Fish Board data highlighted (Figure 7.6). Long-term trends in the rainfall data are indicated by a line of best fit. A time series of barramundi landings for each depot was plotted to identify any concurrent trends between regions (Figure 7.7). A scatter plot of each of the selected long-term climate indices versus Fish Board landings was generated for lags of up to five years to identify any obvious relationships (Appendix 5).

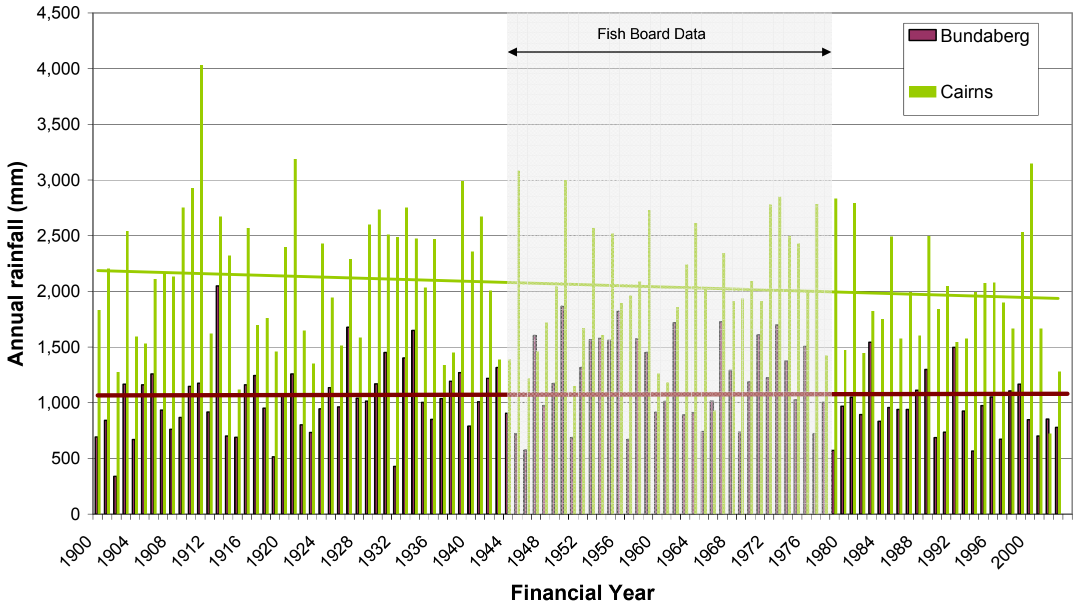


Figure 7.6 Annual financial year (1 July – 30 June) rainfall at Cairns in the north of the study area and Bundaberg in the south (1900/01 – 2003/04). The corresponding period of available Fish Board data is shaded (1945/46 – 1980/81). The long-term trends in rainfall for each location are indicated (lines).

Rainfall for the southern section of the study area is less than that in the far north – an average of 1075 mm at Bundaberg compared to 2063 mm for Cairns. The downward trend in long-term rainfall at Cairns reflects a general drying along the east coast of Australia over the past 100 years (BOM 2005). The period for which Fish Board data is available appears to cover most of the variability in rainfall during the century. At Bundaberg 1950 was the wettest year on record (1 867 mm) and 1978 the third driest year (573 mm). For Cairns, 1950 was the fifth wettest year (3000 mm) and 1966 the second driest year (929 mm).

The time series plot of Fish Board barramundi landings by region showed a degree of coherency indicating the possibility of a large-scale climate oscillation with a spatially extensive influence. Total north-east Queensland barramundi landings show what appears to be a near decadal cycle in catch across the region (Figure 7.5).

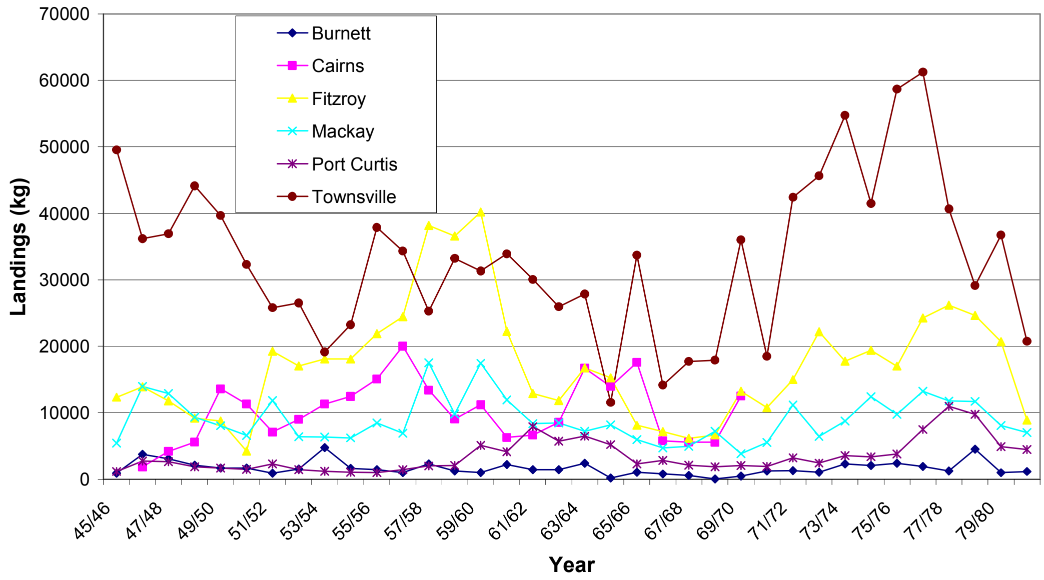


Figure 7.7 Annual financial year (1 July – 30 June) Fish Board barramundi landings for each depot in north-east Queensland (1945/46 – 1980/81). Data excludes catch from the Cairns region for the years 1970/71 – 1980/81.

Correlation matrix

As in the short-term analysis, a correlation matrix of climate indices was generated to check for collinearity between variables. None of the indices were significantly correlated with any other index ($p < 0.05$). A correlation matrix of landings by region returned a number of significant correlations indicating catch is similar across some regions (Table 7.4).

Table 7.4 Pearson correlation coefficient (r) matrix of annual Fish Board regional barramundi landings across north-east Queensland. Correlations significant at the $p < 0.05$** level and at the $p < 0.10$* level.

Regional Landings	Burnett	Cairns	Fitzroy	Mackay	Port Curtis	Townsville	Total
Burnett	1.00						
Cairns	-0.18	1.00					
Fitzroy	0.15	0.26	1.00				
Mackay	0.35**	-0.22	0.65**	1.00			
Port Curtis	0.16	-0.09	0.24	0.34**	1.00		
Townsville	0.17	0.07	0.18	0.26	0.12	1.00	
Total	0.27	0.37*	0.78**	0.67**	0.29*	0.68**	1.00

Lag Analysis

A cross correlation matrix between Fish Board landings (regional and total) and long-term climate indices for lags of up to five years was generated (Table 7.5). Fish Board barramundi landings were significantly and negatively correlated with the QBO at lags of three and four years and significantly correlated with the *L*-index at lags of one through to four years with a peak in significance at three years. Neither the SAM nor the IPO showed any significant correlations with Fish Board landing for lags of up to five years.

Table 7.5 Pearson correlation coefficient (r) between long-term climate indices and Fish Board barramundi landings for north-east Queensland (zero – five year lag). Correlations significant at the $p < 0.05$** level and at the $p < 0.10$* level.

Variable	Year of catch	1 year lag	2 year lag	3 year lag	4 year lag	5 year lag
IPO	0.23	0.17	0.16	0.24	0.18	-0.11
QBO	0.08	-0.22	-0.32	-0.40*	-0.42**	-0.24
SAM	-0.06	0.05	0.13	0.18	0.28	0.16
L-index	0.25	0.45**	0.48**	0.52**	0.41**	0.32

Time series graphs

A time series plot of Fish Board landings against the *L*-index three years previous (the lag with the highest correlation) was generated (Figure 7.8). To smooth the signal, the moving three year average *L*-index was plotted – a technique that shows the relationship in a long-term cycle such as this quite clearly (as per. Robins, Halliday *et al.* 2005).

4.6 DISCUSSION

This chapter examines whether there is a link between long-term climate variables and barramundi catch across north-east Queensland. A significant relationship between the two may provide fisheries managers with the opportunity to predict regional catch a number of years in advance, and so improve the capacity to sustainably harvest the resource.

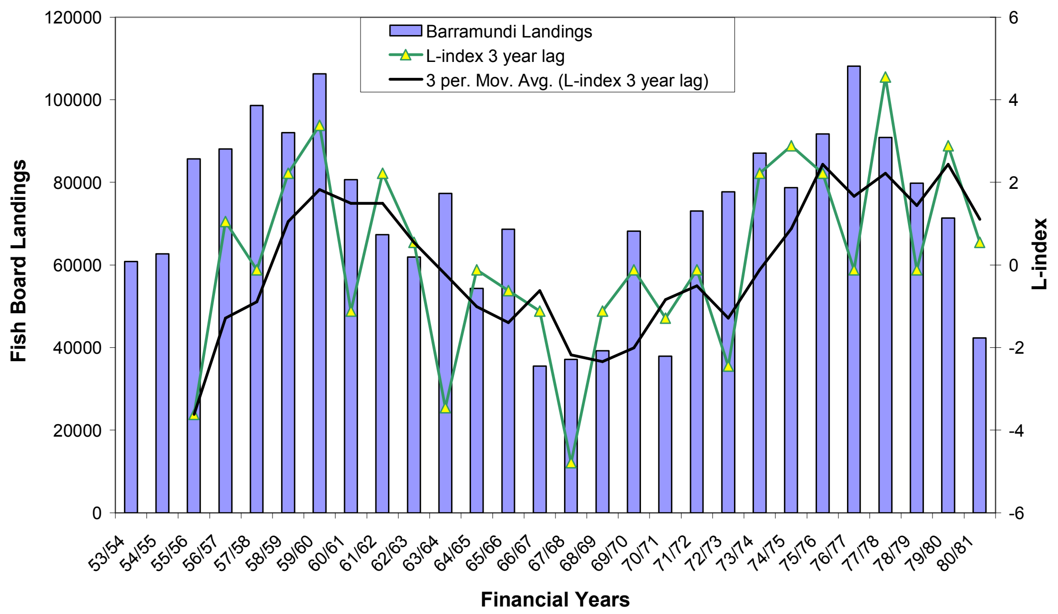


Figure 7.8 Fish Board barramundi landings for north-east Queensland (1953/54 – 1980/81) versus the *L*-index (three years previous). The three year moving average of the three year lagged *L*-index is also plotted to smooth the signal (3 per. Mov. Avg. (L-index 3 year lag)).

A time series plot of barramundi landings from Fish Board depots along the coast showed some degree of simultaneous variation over the period of the study. Catch from every region along the coast (except the Burnett) was significantly correlated with total catch for north-east Queensland. The Mackay region was correlated with all regions to the south (Fitzroy, Port Curtis and Burnett) at the $p < 0.10$ level. These results reinforce the observation that there are coherent variations in catch across the north-east Queensland region. Although it is possible that these variations are driven by other influences such as changes in fisheries management, capture technology or anthropogenic impacts rather than large-scale climate cycles, it is considered unlikely that such impacts would extend across 1 500 km and 35 years. However, without detailed information on these other influences it is not possible to know for sure. All of the significant correlations between catch and long-term climate variables occurred at a lag of one or more years indicating that the effect from long-term climate variability is strongest on early life cycle stages of the fish and less so on catchability.

The relationship between the IPO and Fish Board catch was not significant at any of the lags tested. Previous studies have shown the IPO to drive synchronous, large-scale variations in northern hemisphere pelagic fishery catch (e.g. Klyashtorin 1998).

However, in most cases this is a result of basin scale changes in winds, upwelling, primary production and nutrient levels (see review by Chavez, Ryan *et al.* 2003; Ottersen, Planque *et al.* 2001). These changes are stronger in the northern hemisphere and regions adjacent to the South Pacific Convergence Zone in the southern hemisphere, and less along the north-east coast of Australia and so may not affect inshore areas (Folland, Parker *et al.* 1998). The relationship between the IPO and flow or rainfall in the region has not been found to be significant (e.g. Jones and Everingham 2005; Micevski, Franks *et al.* 2006) and so influences from the terrestrial system may also be minimal. With respect to the modulation of cyclone incidence across the region, the period of Fish Board data (1945/46 – 1980/81) unfortunately corresponds almost entirely with a negative phase of the IPO when the relationship with tropical cyclones off the coast of north-east Queensland is not significant (as opposed to the positive phase of the IPO) (Grant and Walsh 2001). In other words, there is no significant relationship between cyclone incidence across north-east Queensland and the IPO for the years of this study, and so influences on the fishery as hypothesised are therefore unlikely. It could be that during periods when the IPO is in a positive phase the correlation between the IPO and barramundi catch across the region may be stronger.

Correlations between catch and the QBO were negative and significant at a lag of three and four years when most barramundi are fingerlings or juveniles in the nursery areas. As with the IPO, the QBO has been linked to changes in tropical cyclone activity (Gray and Scheaffer 1991). An increase in the frequency of intense tropical cyclones in the south-west Pacific Ocean (near Australia) is seen during westerly phases of the QBO (positive values of the QBO index) and so a negative correlation with catch three or four years later would suggest that the effect of cyclones on early barramundi life cycle stages is destructive. Results from the analysis of short-term climate variables (Chapter 4) and threshold events (Chapter 6) indicated that increased wet season rainfall and flow had a likely positive effect on survival of young-of-year fish and subsequent catch, but that extreme pre-wet season rainfall and early dry season flow negatively affected survival of fish and reduced subsequent catch, a result that would concur with the negative correlation seen here. The hypothesis that cyclones would increase catch in the year of catch (by flushing mature males into the commercial fishery) is positive as predicted, although, not significant.

Although previous analyses have indicated that the QBO modulates the incidence of cyclones in the western Pacific (e.g. Gray and Scheaffer 1991), there are some who argue that a convincing causal mechanism linking the two is not yet provided (e.g. Baldwin, Gray *et al.* 2001). If this were the case, a connection between the QBO and another climate variable (rather than cyclones) may explain the significant correlations seen here. A strong relationship between the January – February QBO and the solar cycle (and LSTR) is noted in one study (e.g. Salby and Callaghan 2000) and is thought to be the result of changes in the strength of the northern hemisphere polar vortex. However, the Pearson's correlation matrix of all the long-term climate indices used in this analysis did not show any significant correlations, and so a significant relationship between the QBO and *L*-index variables in this study is dismissed. There is also some suggestion that the rate of QBO westerly descent is enhanced during warm phases of ENSO (El Niño events) and so there may be some interaction between these two systems, although, relationships if present would not be linearly correlated (Baldwin, Gray *et al.* 2001).

The hypothesis that barramundi catch would be positively correlated with the SAM was correct in sign for all but the year of catch, although correlations were not significant. The hypothesis suggests that wetter conditions and enhancement of nursery habitats would be linked to the SAM across the north-east Queensland region. The variable used in this analysis was the average SAM for the full financial year as connections with tropical climatology are as yet unclear (Sturman and Tapper 1996). Matthews and Meredith (2004) have reported that anomalous surface westerlies appear around Antarctica approximately one week after anomalous convection in the equatorial Indian Ocean in association with the Madden-Julian Oscillation (MJO). In the short-term analyses, the correlation between the November – April MJO phase 6 (enhancement of rainfall) and barramundi catch in Princess Charlotte Bay was significant and positive at a lag of one year. It could be, then, that an average November - April value of the SAM index might return a stronger correlation with barramundi catch across the region or a longer time-series of data may strengthen the correlations.

The strongest and most consistent positive correlations with barramundi catch were with the *L*-index. High values of the *L*-index indicate that the high pressure belt is anomalously south, a pattern that tends to generate increased rainfall along the north-east coast. Correlations were highest at a lag of three years, when fish are likely to be spawning and in their early life cycle stages. The significant correlation at one, two and four years are probably because fish are maturing at different ages (two – four years). In the literature to date there are no reports of a significant relationship between the LSTR and climate variables other than rainfall (e.g. freshwater flow or wind) across north-east Queensland. It may be, then, that other climate variables found to be significantly correlated with catch in the short-term analysis are affected by the LSTR.

Other studies that have shown a connection between the LSTR and fisheries catch in Australia examined changes in the strength of the zonal westerly winds across southern Australia. In each case, increases in wind speed improved the survival of early life stages of the fish via favourable larval transport or increased plankton productivity (Jenkins 2005; Thresher 1994). In the case of the barramundi, however, increased wind across the region (as would be expected with a southerly displacement of the sub-tropical ridge) is likely to increase evaporation and lead to reduced young-of-year survival in the nursery habitat (i.e. a negative correlation). In the Fitzroy River area too, the long-term cycle in barramundi catch was ascribed to changes in freshwater flow (Robins, Halliday *et al.* 2005). If this was the case, the positive correlation between the *L*-index and barramundi catch is an indication that the LSTR is generating conditions conducive to early and continued life cycle survival.

In summary, most of the relationships between long-term climate cycles and Fish Board barramundi landings proposed in the original hypothesis were accurately predicted and some were significant (Table 7.6). This interpretation assumes that growth of most barramundi to commercial size occurs in two to four years (as indicated in the life cycle model and results from the analysis of short-term climate variables) as correlations prior to four years were not significant.

The results show that long-term climate cycles are significantly correlated with spatially extensive, long-term catch of barramundi across north-east Queensland. Both the QBO and LSTR were significant three and four years prior to catch – a lag that corresponds with the early life cycle stages of the fish. These findings suggest that there may be an opportunity to predict the impact of climate on the barramundi fishery a number of years in advance as has been done for the pelagic fisheries of the world.

Table 7.6 A summary of the correlation analysis compared to the hypothesis linking long-term climate cycles and commercial barramundi catch as recorded by north-east Queensland Fish Board depots. As in the original hypothesis, cycles that were expected to correlate with increased population and therefore catch are indicated by a "+" sign while those that were expected to decrease survival and subsequent catch are indicated by a "–" sign. Climate variables that are not linked in the life cycle model to the developmental stage of the fish are marked as not applicable (n/a). Relationships that were significant at the $p < 0.10$ level or above, and confirm the original hypotheses, are shaded in grey. Those that were not significant are left without highlight. There were no correlations that were significant and opposite in sign to that hypothesised.

Life cycle stage / Climate index	Spawning	Larvae	Fingerlings	Juveniles	Maturing males	Returning males
IPO	n/a	n/a	-	-	+	+
QBO	n/a	n/a	-	-	+	+
SAM	n/a	n/a	+	+	+	+
L-index	n/a	n/a	+	+	+	+

7.7 CONCLUSION

Analysis of long-term barramundi landings as recorded by the Fish Board across north-east Queensland identified synchronous long-term variations in catch for many regions along the coast. Correlations between barramundi catch and indices of the QBO were significant at lags of three to four years and between barramundi catch and the LSTR one to four years prior to catch. The results indicate that these climate cycles may be affecting the early life cycle stages of the species by influencing climate variables identified in the analysis of short-term climate effects. There may be an opportunity to predict the impact of long-term climate cycles on the barramundi fishery of north-east Queensland a number of years in advance.

CHAPTER 8: PREDICTIVE MODEL DEVELOPMENT

"All models are wrong, but some are useful." George Box, 1978.

8.1 INTRODUCTION

Traditionally, the modelling of a fishery in order to develop guidelines for a sustainable harvest assumed that fishing pressure had the greatest effect on population. As a result, there has been a focus on the development of surplus production/yield models that use catch and effort data (e.g. Fox 1970), and more complex age-structured models that require age class data including recruitment and mortality (e.g. Fournier and Archibald 1982). More recently, attempts have been made to include the effects of variations in climate on the catch of fisheries by introducing climate variables into catch models (e.g. Meynecke, Lee *et al.* 2006). This chapter addresses research question 7: How much of the variability in barramundi catch can be predicted on the basis of climate variability? First, a review of the current state of barramundi modelling (including the use of climate data), was undertaken to consider the options for modelling barramundi catch in Princess Charlotte Bay where there is no age structure data. Second, a predictive model based on the relationships between catch adjusted for effort and short-term/extreme climate events identified in Chapters 4 and 7 was developed for the fishery.

8.2 EXISTING BARRAMUNDI FISHERIES MODELS

Grey and Griffin (1979) undertook the first barramundi population modelling in Australia using the Schaefer surplus production model (Schaefer 1954) in response to a 70% fall in Northern Territory catch between 1975 and 1978. Using catch and effort gridded fishery data from 1972 – 1978 to calculate maximum sustainable yield, results indicated that the fishery was being over-exploited and recommendations to introduce a series of management measures were made. Outputs were improved by using the surplus yield model methods of Fox (1970; 1975) and by assessing the fishery as a number of separate units rather than as a single stock (Griffin 1986). The later inclusion of rainfall totals for a single local station in the Daly River catchment of the Northern Territory, and the Gulf of Carpentaria (GOC) further improved outputs, although, other measures of climate have not been included (Griffin 1993). The most recent barramundi stock assessments in the Northern Territory used derivations of the Deriso delay-difference model and included age, growth and habitat parameters (Griffin and Kelly 2001). Results were more accurate than earlier models, however, it was noted that there was considerable scope for improving the estimate of habitat area (Roland Griffin, Fisheries Researcher, Northern Territory Department of Primary Industries, pers. comm. June 2002). Additionally, it has been determined that catch selection in the species does not follow a normal distribution (Griffin 1986) and, due to their high fecundity, adequate recruitment may be maintained by a limited number of females, thus limiting the relationship between adult stock densities and recruitment used in population models (Davis 1984).

In Queensland, the Tropical Resource Assessment Program (TRAP) records annual catch and catch per unit effort (CPUE) for thirteen of the most important fishery species. Use of the CLIMPROD model (a surplus production model with the addition of an environmental variable) to model barramundi in the north-east of the state indicated that the maximum sustainable yield was higher than was being fished (Magro, Gribble *et al.* 1997). However, inconsistencies in the model and the short time series limited the reliability of results and the model explained only 10% of the variance in abundance. The introduction of rainfall as a variable did not increase the fit or reliability of the model (Magro, Gribble *et al.* 1997). However, it was suggested by the authors that the inclusion of other climate variables that might impact on the fishery (such as freshwater flow) may improve the accuracy of outputs. In contrast, a more recent study using the CLIMPROD model reported an improvement in the results when rainfall or the SOI were included for populations of barramundi along the east coast of Queensland (Meynecke, Lee *et al.* 2006).

Tagging studies of barramundi in the Norman River of the GOC, provided size-frequency distribution data for inclusion into a population dynamics model developed by Hall, Gribble *et al.* (1998). Distributions were normal, relatively stable over the period of the study (1983 – 1998) and dominated by fish in the 55 – 70 cm total length class (three to four year age class as calculated from total length using the von Bertalannffy growth curve model). However, lower and upper size and age distributions were variable across years, and results indicated that mortality was not related to CPUE or annual rainfall. In summary, limitations in fisheries population models result in varied outputs when applied to a barramundi fishery, and the inclusion of a single climate parameter gives mixed results depending on the location and model used.

In the Fitzroy River area, correlation and regression techniques were used to examine the relationships between rainfall, freshwater flow and catch (Robins, Halliday *et al.* 2005). Best subsets regression returned two models. Both included catch and effort, summer rain in the year of catch, and a stocking variable four years prior to catch. The first also included summer rainfall four years prior to catch (R^2 = 88.02; n = 35) and the second summer flow four years prior to catch (R^2 = 86.96; n = 35). However, it was effort that explained the significant proportion of the variation ($r = 0.76$, $p < 0.01$) precluding the option to use the model in a predictive capacity, and the validity of using variables four years prior to catch was questioned by the authors. Regression models using long-term Fish Board data accounted for up to 39% of the variance in landings but again included a variable in the year of catch and so had no predictive capacity.

The validity of using correlative and regression techniques as an alternative to production/yield models is discussed in a comparative paper by Stergiou and Christou (1996) who tested a suite of eight regression, univariate and multivariate time series modelling techniques to forecast annual commercial fisheries catch in Greek waters. The authors concluded that a simple multiple regression model incorporating climate variables performed better in terms of fitting accuracy than other techniques tested, including the Fox surplus yield model. However, it must be noted that correlative relationships may change over time if the causal mechanism is not embodied in the model (Solow 2002). This limitation of correlative and time series modelling must be compensated for through the use of sound theoretical and life cycle modelling that explains the causal links, and eliminates irrelevant variables from the analysis (Robins, Halliday *et al.* 2005). Without age structure data for inclusion in a surplus production or population dynamic model, forward stepwise ridge regression was used here to determine how much of the variance in barramundi catch in Princess Charlotte Bay can be explained by climate parameters.

8.3 DATA

Climate and barramundi catch data used to develop the statistical models were those used in the analysis of short-term climate effects (Chapter 4, Table 4.6). The life cycle model was consulted when selecting climate variables for inclusion in the modelling of barramundi catch. Variables that affect the spawning and nursery habitats (two years prior to catch), the maturing males (one year prior to catch), and the catchability of adults (in the year of catch) were all included (Table 8.1). Although some of the climate variables were significantly correlated with each other ($p < 0.05$), there was not always an obvious causal link to explain the relationship, and in some cases variables may have affected the fishery in different biological ways. Because of this, it was considered valid to include all the climate variables selected in the statistical modelling (as per Robins, Halliday *et al.* 2005).

8.4 METHODS

Systems dynamic model

Initially, a conceptual systems dynamic model was constructed to clarify climate influences on barramundi catch. Systems dynamic models explain complex systems and allow for the inclusion of non-linear relationships through the use of internal feedback loops, time delays and a system of stocks and flows (Ford 1999). These features would provide the capacity to model the complex interactions between climate and the barramundi fishery identified in Chapters 4 and 6.

Table 8.1 Variables included in the statistical modelling of Princess Charlotte Bay barramundi catch. Each variable is considered to have a biologically relevant effect on the fishery as defined by the life cycle model (Chapter 3, Figure 3.2). SST = sea surface temperature.

Year of catch (catchability)	One year prior to catch (maturing males)	Two years prior to catch (spawning and nursery habitats)
Rainfall October – December	Minimum temperature July	Maximum temperature December
Rainfall January – March	Rainfall July – September	Rainfall July – September
Rainfall April – June	Rainfall October – December	Rainfall October – December
Flow October – December	Rainfall January – March	Rainfall January – March
Flow January – March	Rainfall April – June	Rainfall April – June
Flow April – June	Flow July – September	Flow July – September
	Flow October – December	Flow October – December
	Flow January – March	Flow January – March
	Flow April – June	Flow April – June
	Evaporation annual	Annual evaporation
		Average October – December SST
		Average January – March SST

Statistical models

As there is no age structure data available for barramundi in Princess Charlotte Bay to support the use of more complex models, statistical modelling was employed to quantitatively determine how much of the variance in barramundi CAE could be explained by the climate variables. The first model built used only climate variables that affected the spawning and nursery habitats two years prior to catch (Predictive Model I) and so provided a forecast of future catch that would allow for a management response. Collinearity between variables was compensated for through the use of forward stepwise ridge regression (FSRR) (StatSoft. Inc. 2005), a process that tests the residuals from each model step before selecting the next variable, therefore ensuring that only variables that improve the model are included. The ridge regression coefficient (k), selected to ensure model coefficients were stable, was set at 0.10 as a ridge trace did not indicate a significant change in adjusted R^2 values with higher values of k. Due to the limited number of observations (12 years), the process was limited to only two steps to reduce the possibility of over-fitting.

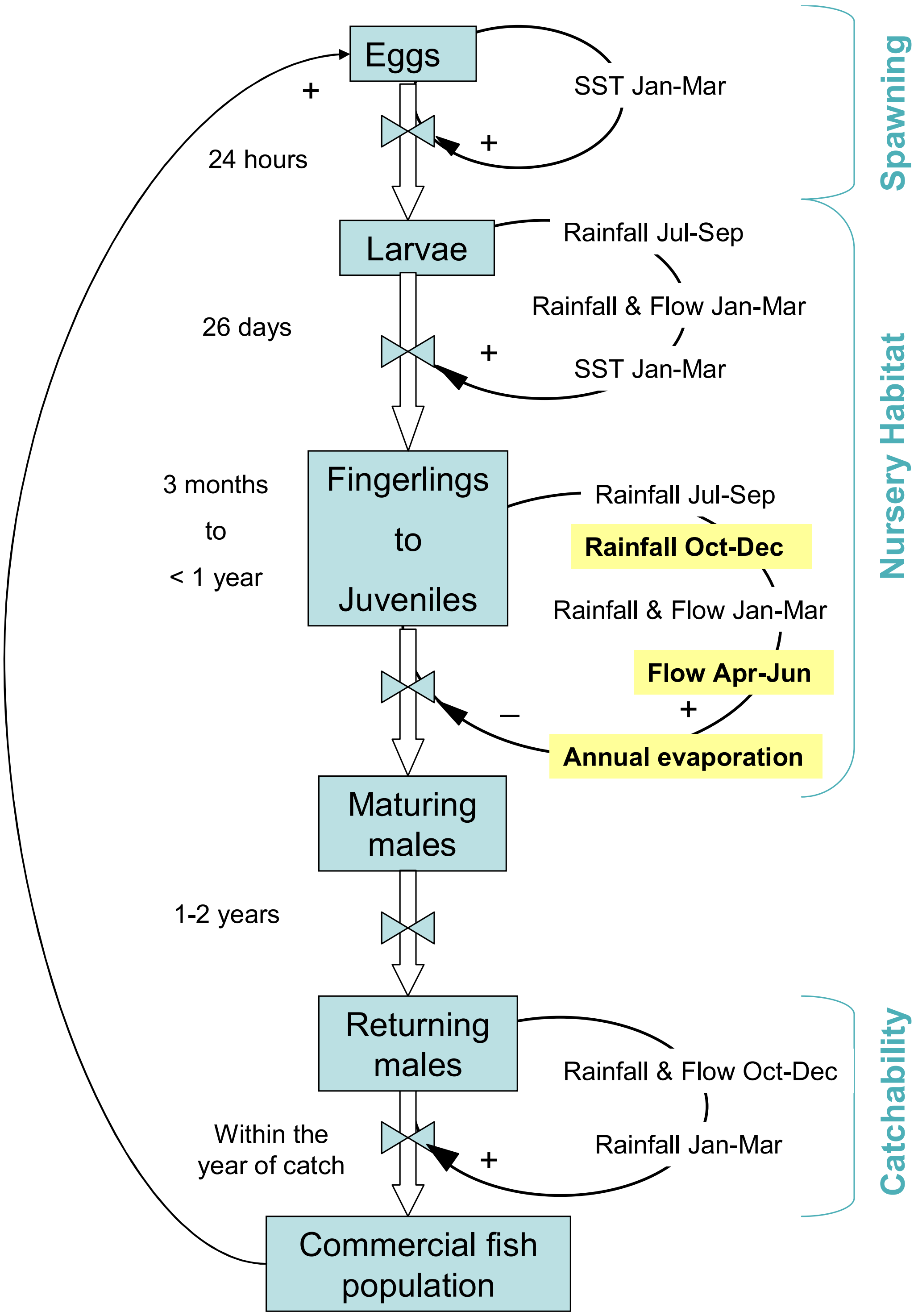


Figure 8.1 A conceptual systems dynamic model of climate influences on the Princess Charlotte Bay barramundi fishery. Climate variables that were significantly correlated with barramundi catch adjusted for effort (CAE) ($p < 0.05$) are included to the right of the stock and flow chart, and time delays are shown on the left. Climate variables that have significant, non-linear correlations with CAE are highlighted in bold.

The second model (Predictive Model II) aimed to optimise the amount of variance in CAE explained and so climate variables affecting the early life stages of the fish, the maturing males, and catchability (i.e. lags of up to two years prior to catch) were all included in the process. The ridge regression coefficient (*k*) was again set at 0.10 and the number of steps was increased to three. For each model residuals were checked for normality using a probability plot and autocorrelation using the Durbin-Watson statistic (StatSoft. Inc. 2005).

The predictive capability of regression-based models has been questioned by several authors including Stergio and Christou (1996) and Myers (1998). For this reason, the robustness of a predictive regression model needs to be tested by using cross validation (e.g. Wilkes (1995) and the data-splitting concept recommended by Myers (1998)). In these analyses, each model was cross validated using a "leave-one-out" (LOO) technique (Wilkes 1995) that compares the sum of squares of the original model residuals with the sum of squares for the deleted residuals (residual value for the respective case, had it not been included in the regression analysis, that is, if this case was excluded from all computations) (Equation 8.1). This technique results in a cross validated predictive R^2 value, and was used as a measure of the predictive capability of the model (Balston and Williams 2005).

$$\text{Predictive } R^2 = 1 - \frac{SSEdeleted}{SST} \qquad (8.1)$$

where $SSEdeleted = \sum_{i=1}^{n} (y_i - \hat{d}_i)^2$

y_i is the ith observed value

$\hat{d}_i$ is the predicted value when y_i is not included in the analysis.

8.5 RESULTS

In the conceptual systems dynamic model (Figure 8.1), stocks were defined as the life cycle stages of the fish identified in the original hypothesis (Chapter 3, Table 3.2) from spawning (eggs), through to commercial catch. Climate variables were those identified in the life cycle model and by both linear and non-linear statistical analyses as being significantly correlated with catch. Flows from one life cycle stage to the next are affected by the climate influences either positively or negatively and were marked as such. Time delays are indicated to the left of each flow. For simplicity, other factors such as predation, natural mortality, competition and fishing effort were not included in the model. Ideally, with enough years of data, a statistical model could incorporate the range of significant variables illustrated by the conceptual systems dynamic model. However, with limited years of observed catch, the number of variables in each statistical model was restricted to avoid over-fitting.

The forward stepwise ridge regression model ‘Predictive Model I’ built from variables likely to affect spawning and nursery habitats two years prior to catch included dry season (July – September) rainfall and annual evaporation each two years prior to catch. The model explained 62.4% of the variance (adjusted R^2) in Princess Charlotte Bay CAE (Equation 8.2, Table 8.2). The adjusted R^2 takes into account collinearity between variables and the degrees of freedom in the model.

$$CAE = 29358.08+7771.86\,(RJS)-0.01(E) \qquad (8.2)$$

where RJS is *Log N*(total July – September rainfall 2 years prior to catch +1)
E is (total annual evaporation 2 years prior to catch)^2

Residuals for Predictive Model I although slightly curved were normally distributed, independent (according to the Durbin-Watson statistic; $p < 0.05$) and fell within + 2 standard deviations of the mean indicating an absence of outliers. Predicted versus observed values of catch were plotted (Figure 8.2). Cross validation of the model using the LOO technique returned an R^2 value of 58.6%. This demonstrates the robustness of the model and indicates that even when used in a predictive capacity, the model explained more than half the variance in Princess Charlotte Bay barramundi CAE (Figure 8.3).

Table 8.2 Predictive Model I developed to provide an estimate of future Princess Charlotte Bay barramundi catch adjusted for effort (CAE) from climate variables two years prior to catch (nursery habitats). The adjusted R^2 takes into account collinearity between variables and the degrees of freedom in the model.

Predictive Model I (Adjusted R^2= 0.6237)	B	Standard Error	*p*-level
Intercept	29358.08	20959.81	0.19
Log N (Total rainfall July – September 2 year lag +1)	7771.86	2370.64	0.01
(Total annual evaporation 2 year lag)^2	-0.01	0.00	0.06

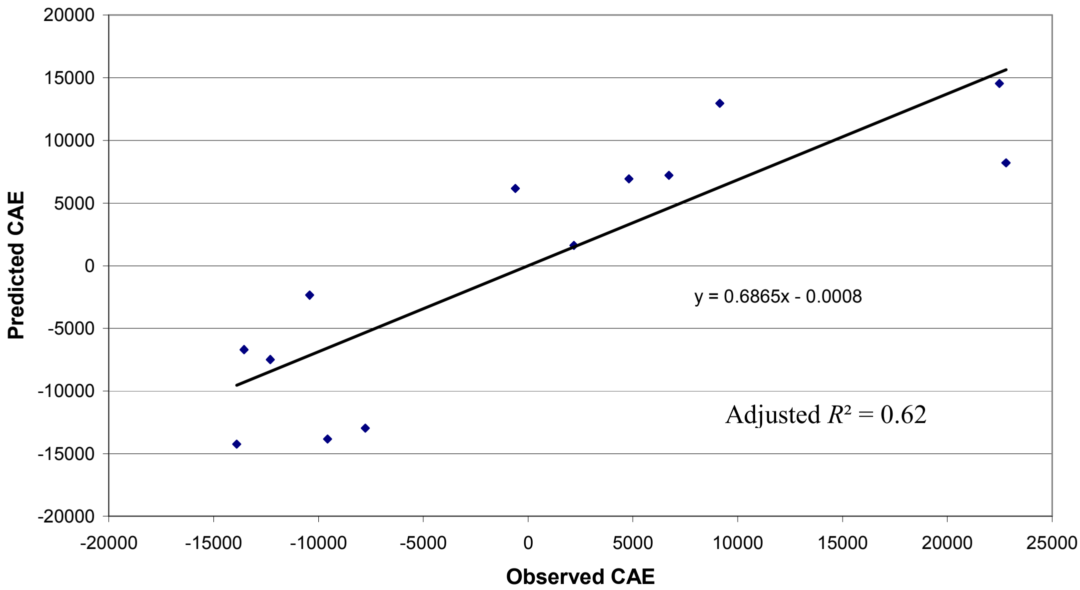


Figure 8.2 Predicted values of Princess Charlotte Bay barramundi catch adjusted for effort (CAE) from Predictive Model I versus observed. Variables in the model are total dry season (July – September) rainfall and total annual evaporation, both two years prior to catch. Linear fit plotted.

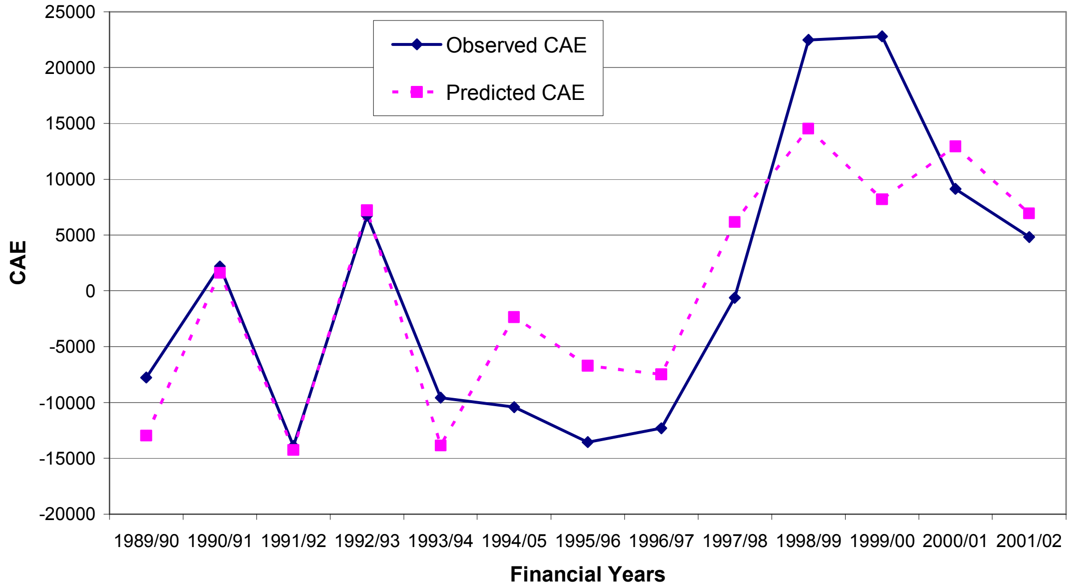


Figure 8.3 Time series plot of predicted and observed Princess Charlotte Bay barramundi catch adjusted for effort (CAE) from Predictive Model I (1989/90 – 2001/02). The model contains the climate variables total rainfall July – September and total annual evaporation both two years prior to catch. Cross validated $R^2 = 0.586$.

Predictive Model II built from all the climate variables identified in the life cycle model as likely to affect subsequent catch included dry season rainfall and annual evaporation two years prior to catch, and early dry season (April – June) flow (in the year of catch). The model explained 69.2% of the variance (adjusted R^2) in Princess Charlotte Bay CAE (Equation 8.3, Table 8.3).

$$CAE = 35739.14+6557.75\ (RJS)-0.01(E)+0.03(FAJ) \qquad (8.3)$$

where RJS is *Log N*(total July – September rainfall 2 years prior to catch +1)

E is (total annual evaporation 2 years prior to catch)^2

F is total April – June flow (no lag)

Table 8.3 Predictive Model II developed to provide an estimate of future Princess Charlotte Bay barramundi catch adjusted for effort (CAE) from climate variables up to two years prior to catch (nursery habitat through to returning males). The adjusted R^2 takes into account collinearity between variables and the degrees of freedom in the model.

Predictive Model II (Adjusted R^2= 0.6920)	B	Standard Error	*p*-level
Intercept	35739.14	19295.76	0.10
Log N (Total rainfall July – September 2 year lag +1)	6557.75	2249.34	0.02
(Total annual evaporation 2 year lag)^2	-0.01	0.00	0.02
Total flow April – June no lag	0.03	0.02	0.11

Residuals for Predictive Model II were again normally distributed, independent and fell within + 2 standard deviations of the mean. Predicted versus observed values of catch were plotted (Figure 8.4). Cross validation of Predictive Model II returned an R^2 value of 61.3% (Figure 8.5). As can be seen from Table 8.3, the inclusion of the third variable did not significantly improve the model ($p < 0.10$) when compared to Predictive Model I.

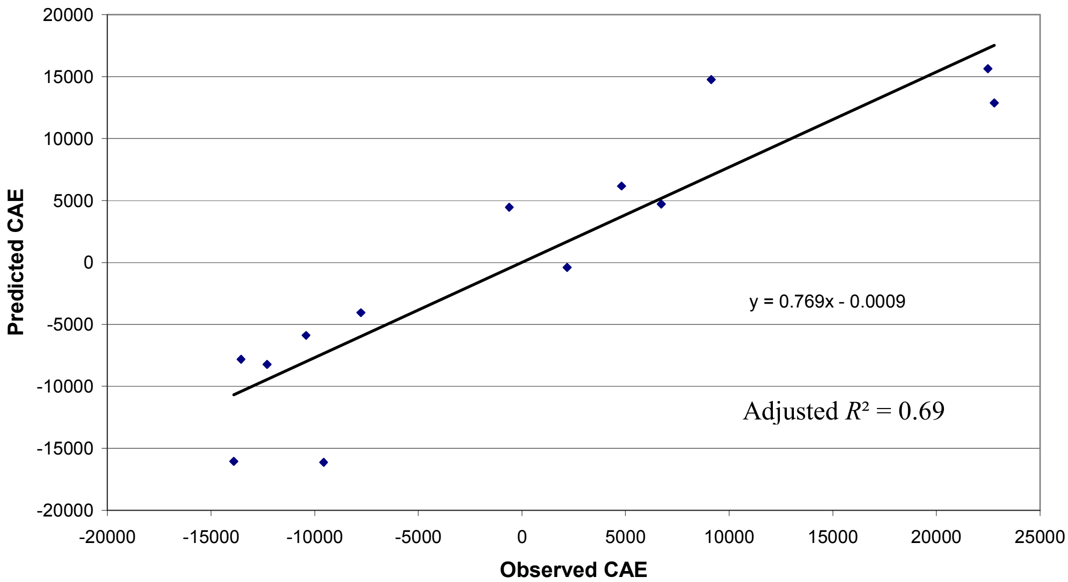


Figure 8.4 Predicted values of Princess Charlotte Bay barramundi catch adjusted for effort (CAE) from Predictive Model II versus observed. Variables in the model are dry season (July – September) rainfall, total annual evaporation (both two years prior to catch) and early dry season (April – June) flow (in the year of catch). Linear fit plotted.

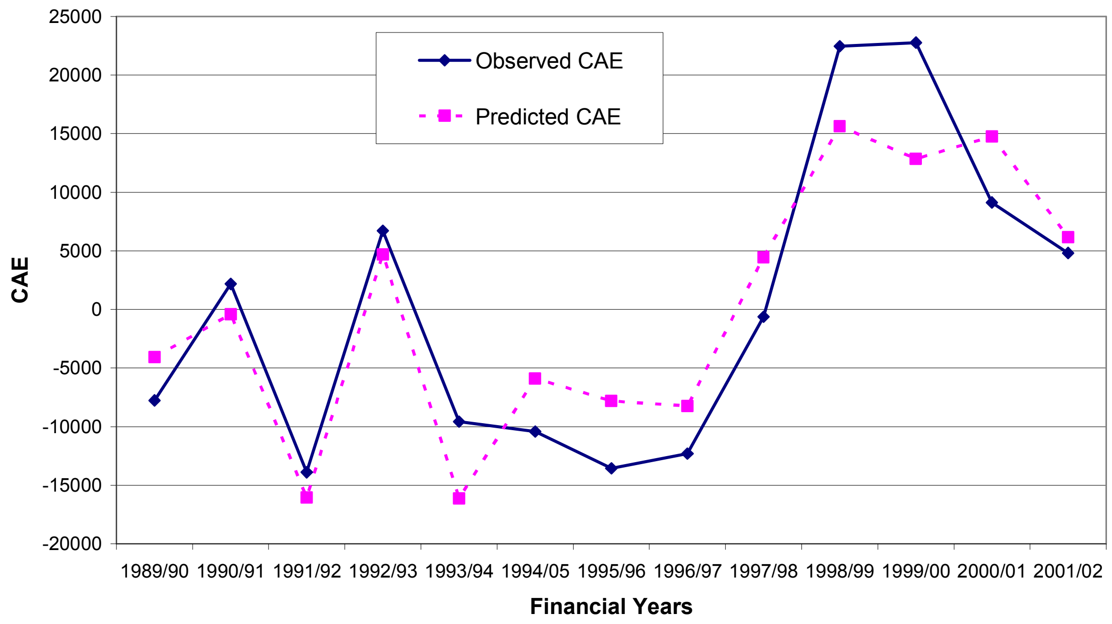


Figure 8.5 Time series plot of predicted and observed Princess Charlotte Bay barramundi catch adjusted for effort (CAE) from Predictive Model II (1989/90 – 2001/02). The model contains the climate variable dry season (July – September) rainfall, total annual evaporation (both two years prior to catch) and early dry season (April – June) flow (in the year of catch). Cross validated R^2 = 0.613.

8.6 DISCUSSION

Results from the forward stepwise ridge regression analyses indicated that more than half of the variance in barramundi catch adjusted for effort (CAE) in Princess Charlotte Bay can be explained by climate variables. In the analyses of short-term climate effects (Chapter 4), dry season rainfall (July – September), wet season rainfall and flow (January – March), annual evaporation and wet season sea surface temperature (SST) were significantly correlated with CAE two years prior to catch. Each of these variables was considered likely to affect the survival of the early life cycle stages of the barramundi in inshore waters and wetland nursery habitats. Predictive Model I contained two of these variables: dry season rainfall and annual evaporation. As discussed in Chapter 4, it is thought that increased dry season rainfall maintains remnant wetland areas throughout the dry season or wets the soil profile prior to pre-wet season rainfall and subsequent habitation by larvae and juveniles. Reduced evaporation throughout the year, and most significantly in the wet season, extends the size and period of wetland inundation and hence viable nursery habitat, and is a variable not considered in any other analysis of climate and barramundi catch. The model returned an R^2 of 62% and a cross validated R^2 of 58%.

In comparison to other regression models of barramundi catch reviewed, this is an encouraging result. A best subsets regression of rainfall and flow in the Fitzroy area explained only 39% of the variance in Fish Board landings (summer rain in the year of catch, autumn flow three years prior to catch and summer rain four years prior to catch) before cross validation (Robins, Halliday *et al.* 2005). When effort and stocking rates were included, up to 88% of the variance in short-term barramundi catch was explained, although, effort accounted for most of the improvement in fit and the predictive capacity of the model was not tested (Robins, Halliday *et al.* 2005). In addition, the inclusion of variables in the year of catch precluded a management response. It should also be noted that four variables in a model based on such a short time series (13 years) would most likely have overfit a predictive model (Bob Mayer, Statistician, Department of Primary Industries and Fisheries, pers. comm. November 2006). The relationship between climate variables and Fitzroy River area catch in this study (Chapter 5) was in most cases not significant, a likely result of anthropogenic impacts to the region. No other predictive regression models of barramundi catch have been developed.

When compared to population dynamics models, Predictive Model I again performs well. The latest modelling of barramundi catch along the east coast using CLIMPROD returned improved goodness of fit parameters when rainfall or the SOI were included (Meynecke, Lee *et al.* 2006). Results for a model that included rainfall were considered by the authors to be robust, although a jackknife R^2 varied from 0.35 (1988 – 2000) up to 0.85 (1988 – 2004) indicating a degree of instability over the time series calculated. The authors note that the Food and Agricultural Organisation of the United Nations (FAO) suggests a conservative R^2 value of 70% as an indicator of significant predictive capacity in a multivariate CLIMPROD model. Results for the Princess Charlotte Bay area were not reported.

The inclusion of a third variable in Predictive Model II (early dry season flow) increased the R^2 to 69% and the cross validated R^2 to 61%. However, inclusion of the variable did not significantly improve the model. As noted, it is likely that including three variables is too many due to the limited degrees of freedom (Bob Mayer, Statistician, Department of Primary Industries and Fisheries, pers. comm. November 2006). For these reasons, and because Predictive Model II requires a variable from the year of catch, the first model (Predictive Model I) was retained as the preferred option for use as a possible management tool.

It is worth noting again at this point the limitations of regression modelling when using them to predict future catch. Unless the model contains variables that have a causal link with catch, results will not be robust when the model is used in a predictive capacity. This problem has been addressed in regression models of other species including banana prawns (*Penaeus merguiensis*) in the GOC where only rainfall was retained as a predictive variable despite other climate parameters showing a significant correlation with catch (Vance, Staples *et al.* 1985). It is essential, then, that the variables included in a predictive regression model conform to the life cycle model of the species, as was done in this study. Secondly, to extend the model beyond the range of the original variables used in the generation of the model risks linear extrapolation of results beyond unidentified non-linear thresholds. In this instance, to introduce an extreme event that was not included in the range of data used in the analyses may result in a significantly different prediction to what occurs in the fishery. Indeed, this is one of the risks of modelling the impacts of climate change when using any regression model based on the current climate, and is an issue discussed further in Chapter 9.

8.7 CONCLUSION

A forward stepwise ridge regression model built from climate variables to determine the proportion of variance in barramundi catch for the Princess Charlotte Bay area included dry season (July – September) rainfall and annual evaporation two years prior to catch and explained 62% of the variance in barramundi catch adjusted for effort (CAE). The cross validated R^2 of 58% shows that even when used in a predictive capacity, the model has explained over half of the variance in barramundi CAE for the Princess Charlotte Bay fishery. Neither of these variables has been included in predictive models of barramundi catch to date, and so this result provides a promising option for the improvement of catch models for the species.

CHAPTER 9: EFFECTS OF CLIMATE CHANGE: PRINCESS CHARLOTTE BAY

“Everyone talks about the weather, but nobody does anything about it”. Mark Twain, 1835-1910.

9.1 INTRODUCTION

Unknown by Mark Twain, it is now understood that increased concentrations of greenhouse gases in the atmosphere as a result of human activities have increased both terrestrial and ocean temperatures. The resultant global warming is expected to alter planetary climate including ocean currents, global atmospheric circulations and the frequency and intensity of rainfall, evaporation, tropical cyclones and other extreme events such as drought. This chapter reviews the likely climate changes for north-east Queensland, and considers the possible impacts of these changes on the barramundi fishery of Princess Charlotte Bay through the use of scenario analysis. Results address research question 8: What are the likely impacts of climate change on barramundi catch?

9.2 BACKGROUND

According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, the atmospheric concentration of all greenhouse gases has risen since the beginning of the industrial revolution. The current levels of CO^2 (379 ppm) and methane (1774 ppb) are now the highest in 650,000 years, and nitrous oxide concentrations have risen by 49 ppb since the late 1800s (IPCC 2007). Increased concentrations of greenhouse gases in the atmosphere enhance the naturally occurring greenhouse effect and further heat the troposphere by allowing short-wave radiation from the sun to heat the earth, but preventing long-wave thermal radiation from escaping back out into space. This process is now validated by surface, balloon and satellite data (IPCC 2007).

Climate Change – Existing Trends

Temperature

The global surface temperature has increased by 0.76 ± 0.2°C since 1850 and eleven of the last twelve years (1995 – 2006) rank among the warmest years of the instrument record (IPCC 2007). Additionally, the years 2002 – 2005 were the second through to the fifth warmest on record (Steffen 2006). Temperatures over land have increased at roughly twice the rate of ocean surface temperatures. The decrease in the global diurnal temperature range noted in the IPCC Third Assessment Report (TAR) (IPCC 2001b) is no longer evident as both maximum and minimum temperatures now appear to be increasing equally (IPCC 2007). The rate of warming over the last 50 years is almost double that for the last 100 years (IPCC 2007).

In Australia, the continental mean annual temperature has increased by ~0.8°C, mostly in winter and spring, and 2005 was the warmest year on record (Steffen 2006). Minimum temperatures are increasing up to 30% faster than maximum temperatures, particularly in the northern half of the continent (Hughes 2003) (Figure 9.1). Average annual SSTs on the Great Barrier Reef have increased by ~0.6°C from 1903 to 1999. Warming has been less in the north (~0.4°C) between 10°S and 14°S, and more in the south (~0.7°C) between 20°S and 24°S (Lough 2001).

Rainfall

Since the beginning of the 20th century atmospheric water vapour has increased several percent per decade, and cloud cover by some 2% (IPCC 2001b). Rainfall across Australia has increased slightly, although on a continent wide basis the trend is not statistically significant due to the high inter-annual variability (Smith 2004). For regions where precipitation has increased (northern Western Australia and central Northern Territory) there has been more rain in summer than winter, probably as a result of increases in heavy rainfall events and the number of rain days (Hughes 2003). However, since 1976 it appears that the frequency and intensity of El Niño events has increased, which has resulted in a rainfall decrease along the east coast, mostly in the summer and autumn months (BOM 2005; Hughes 2003; IPCC 2001b; Salinger, Stigter *et al.* 2000) (Figure 9.2). Historical rainfall records for Cairns (Clewett, Clarkson *et al.* 1994) highlight the degree of inter-annual variability in north-east Queensland and show a slight decrease in rainfall, mostly in the April – June period. However, there is no evidence of a significant change in the river flow regimes of north Queensland (Lough 2005).

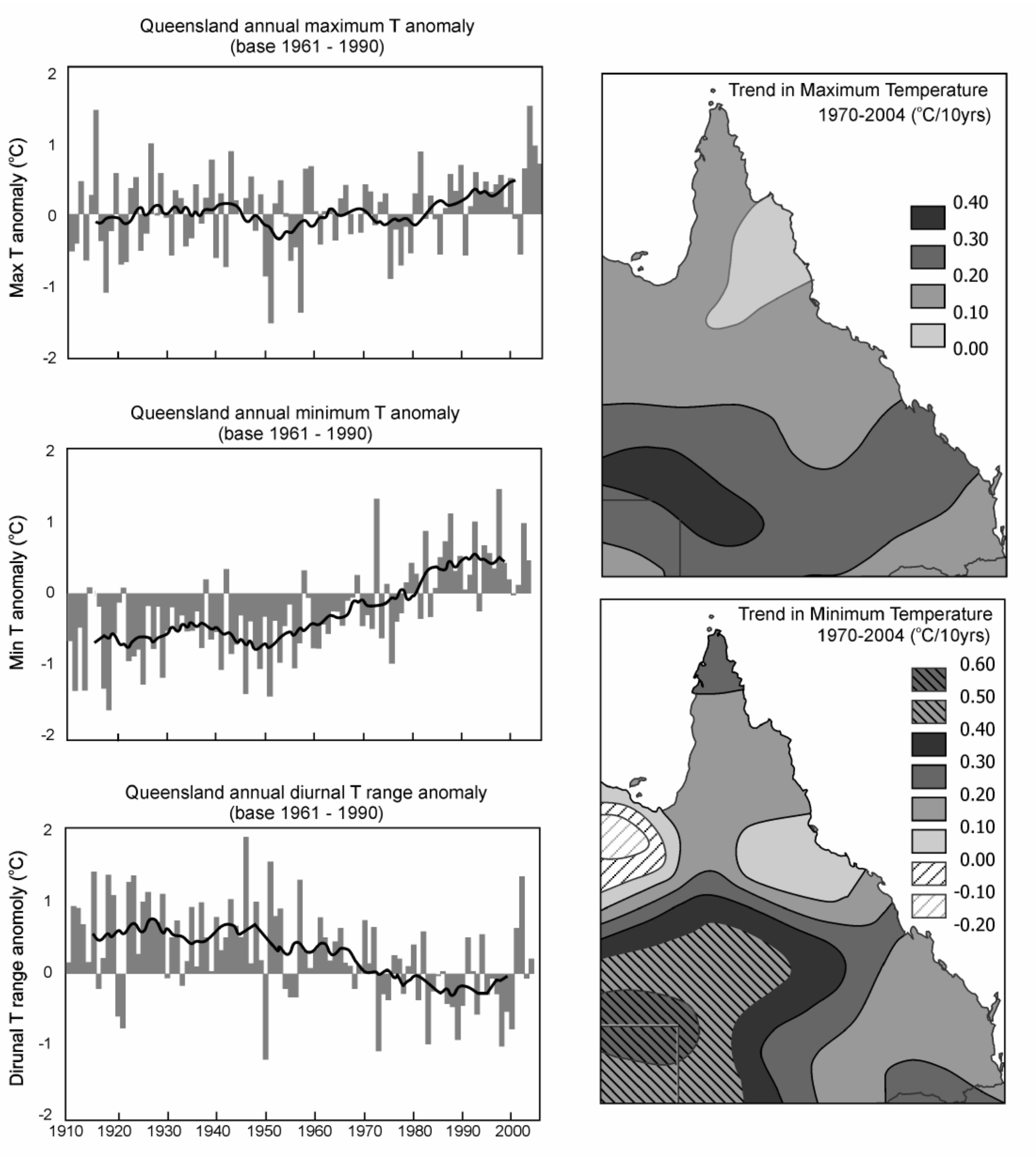


Figure 9.1 Changes in Queensland maximum and minimum temperature and diurnal temperature range. Bar graphs show annual maximum and minimum temperature anomalies and annual diurnal temperature range anomaly from 1961 – 1990. Lines indicate five year running mean temperature. Maps illustrate trends in maximum and minimum temperature (1970 – 2004) in degrees Celsius per decade (adapted from the BOM website 2006).

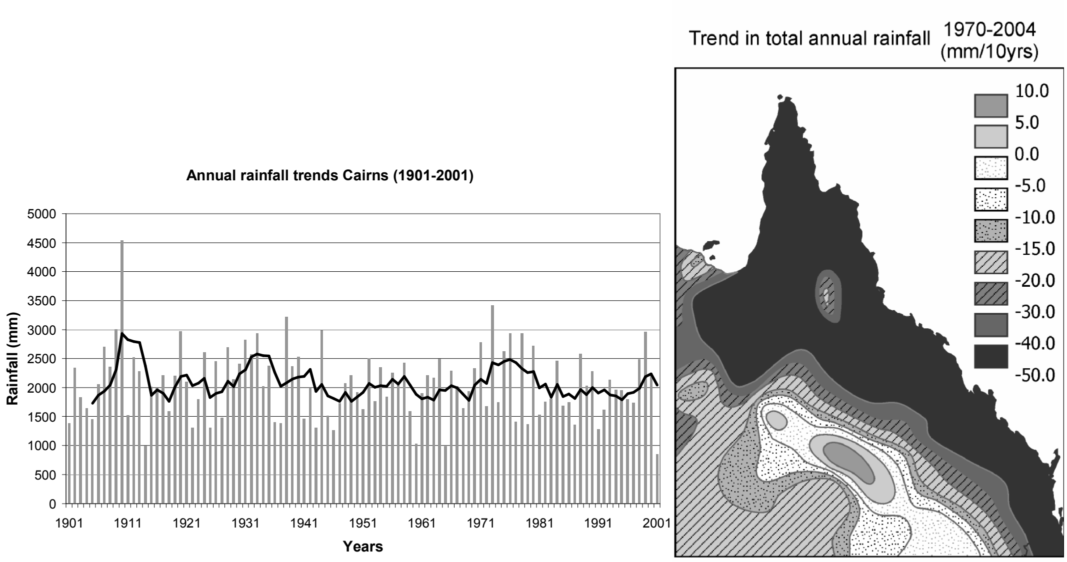


Figure 9.2 Annual rainfall for Cairns (1901 – 2001). The bar graph shows total annual rainfall and the line indicates the five year running mean. The map shows the trends in rainfall across Queensland (1970 – 2004) in mm per decade (adapted from BOM website 2005).

<u>Evaporation</u>

Potential evaporation as measured by Class A pan evaporators did, on average, decline by approximately 4 $mm.yr^{-1}$ across Australia from the early 1970s through to the late 1990s (although values and trends vary by location). The trend was evident even when data was adjusted for the slight increase in rainfall that has been recorded in the same period – an observation that was in agreement with changes seen in many other regions overseas (Roderick and Farquhar 2004). Whether anthropogenic climate change was the cause of this trend is still being debated (Gifford, Farquhar *et al.* 2004). The Penman equation for calculating potential evaporation includes three variables: radiation (light or heat), vapour pressure and wind. Since the early 1900s there had been a slight increase in cloud cover globally, although, the trend in Australia was not sustained over the 30 years of observed pan evaporation decline (Henderson-Sellers and McGuffie 2004). Global dimming (as a result of anthropogenic aerosols and other air-borne particulates including smoke in the atmosphere) had reduced solar radiation reaching the surface of the earth by approximately 1 – 2 $W.m^{-2}$ per decade (1960 – 1990), enough to explain the observed reduction in evaporation (Wild 2004). The role of aerosols in global dimming is still not clear (Stanhill 2004), although, there is some evidence that it affects the structural qualities of clouds (Lohmann and Feichter 2004). However, the reduction in solar radiation observed overseas had not been identified in Australia

(Gifford, Farquhar *et al.* 2004). Finally, a reduction in wind speed has been measured in Australia, although, changes were inconsistent in time and space and not necessarily enough to explain the full reduction in evaporation observed (Linacre 2004). Since 1990, evaporation appears to have increased again, possibly as a result of a decrease in aerosol emissions and an increase in solar radiation in many areas over the same period (Gifford, Farquhar *et al.* 2004; Wild 2004). However, an increase in the number of El Niño events over the same period may explain the change (Gifford, Farquhar *et al.* 2004).

Sea levels

Tidal gauges and satellite altimeter data show an increase in global sea levels of 195 mm since 1870. The most rapid increases (~3 $mm.yr^{-1}$) have occurred since 1993 – a result of both thermal expansion and land-based ice contribution (Steffen 2006). The average rate of sea level rise around Australia is about 1.2 $mm.yr^{-1}$ over the period 1920 – 2000 (Church, Hunter *et al.* 2004). Along the east coast of Queensland levels vary. Over the last 25 years, Townsville and Mackay have recorded a significant increase in sea level (>1 $mm.yr^{-1}$), while Cairns, Bundaberg and Brisbane have recorded a slight drop (Mitchell, Chittleborough *et al.* 2000).

Tropical cyclones

Records from the Australian basin show a decrease in the total number of cyclones since the mid-1960s due to changes in ENSO, but a slight increase in the number of stronger cyclones (Plummer, Salinger *et al.* 1999).

Climate Change – Future Trends

Regardless of efforts to reduce greenhouse gas emissions in the future, much of the climate change over the coming years will be the result of greenhouse gases already in the atmosphere – “committed warming” (ACG 2005; IPCC 2001b). A warmer earth will likely have a reduced equatorial to polar temperature difference, decreased kinetic energy in the atmosphere and a weaker tropical Pacific atmospheric circulation (IPCC 2001b; Vecchi, Soden *et al.* 2006). Generally, conditions will most likely become more humid with more frequent and intense storms in the lower latitudes, and drier conditions in the Australian mid latitudes. Sea levels are expected to continue to rise as polar and continental ice sheets and glaciers melt and the warmer oceans expand (IPCC 2007).

Future climatic conditions are predicted by global climate models (GCMs) that provide a range of estimates based on different scenarios of future greenhouse gas emissions (Feenstra, Burton *et al.* 1998).

Temperature

Mean global temperature is expected to increase by 1.1 to 6.4°C over the 1990 to 2100 period (IPCC 2007). Globally averaged SSTs are also expected to increase with a trend towards a more 'El Niño like' conditions in the central and eastern equatorial Pacific (Cai 2003; IPCC 2001b; IPCC 2007), however, changes to the frequency and intensity of El Niño events are still unclear (IPCC 2007). It is highly likely that hot days and heat waves will become more frequent with greatest increases over land areas (particularly in the Northern Hemisphere) where soil moisture decreases will occur. Cold events and frosts are likely to decrease in frequency (IPCC 2007). An increase in average temperature of between 0.3°C and 2°C by 2030 and 0.8°C and 6°C by 2070 is predicted for Queensland (Walsh, Cai *et al.* 2002). Spatial patterns of warming are expected to be consistent with current observations – greater warming inland and less along the coastal strip (Cai, Crimp *et al.* 2003; Walsh, Hennessy *et al.* 2001) (Figure 9.3). Local scale projections for climate change in the north-east Queensland region have been generated as a subset of the CSIRO scenario analysis for Queensland. Results show an increase in maximum temperature of 0.3°C to 5.2°C for the period 2030 to 2070 (Crimp, Balston *et al.* 2003; Walsh, Cai *et al.* 2002).

Rainfall

Globally averaged atmospheric water vapour, evaporation and precipitation are all projected to increase under climate change. Increases in precipitation are very likely in high latitudes, while decreases are likely in most subtropical land regions (IPCC 2007). Rainfall extremes and intensities are projected to increase almost everywhere. The IPCC TAR stated that there would be an "increase in Asian summer monsoon variability and changes in monsoon strength" as a result of climate change. However, more recent studies have indicated that there is no evidence yet to support this theory (Chase, Knaff *et al.* 2003; Kripalani, Kulkarni *et al.* 2003).

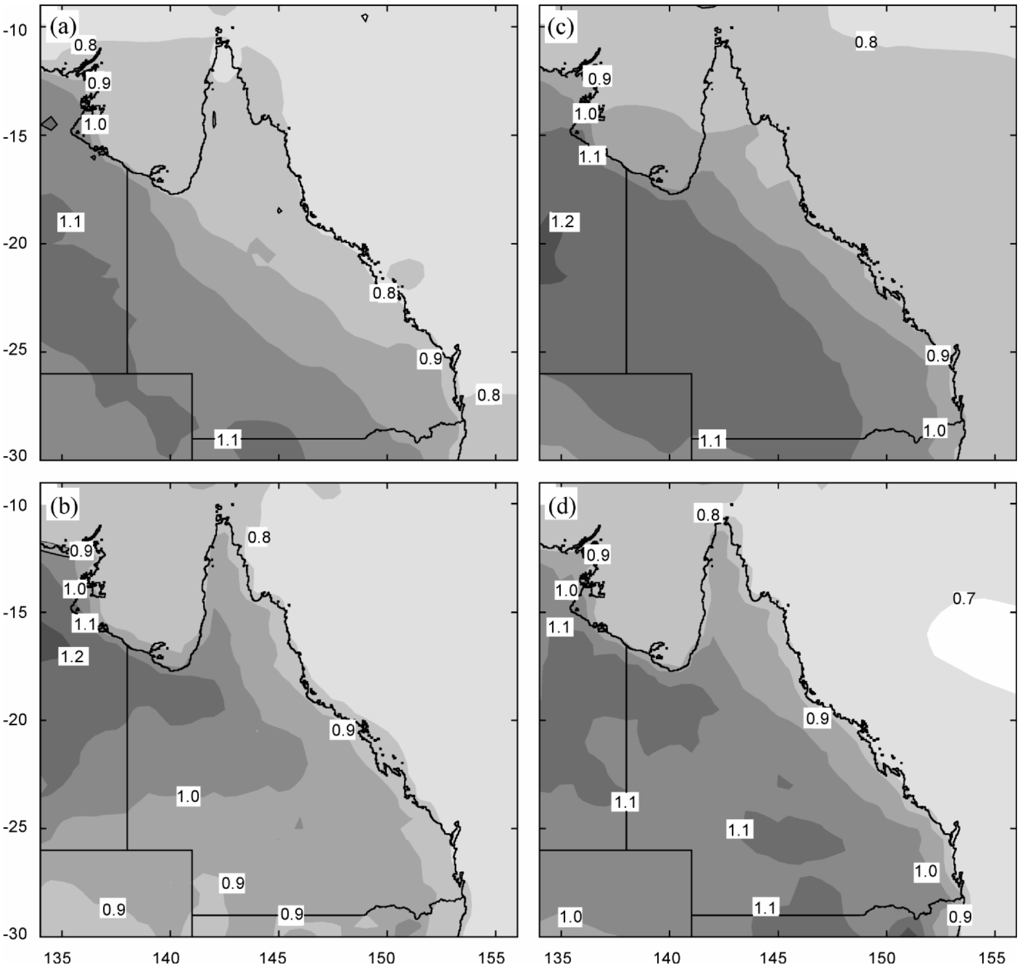


Figure 9.3 Predicted changes in temperature for Queensland per degree of global warming as modelled by the CSIRO DARLAM-60 regional climate model interpolated to a 1 degree grid for (a) summer (December – February), (b) winter (June – August), (c) autumn (March – May) and (d) spring (September – November). Contour interval is 0.1^{o}C (adapted from Walsh, Hennessy *et al.* 2001).

As on the global scale, rainfall projections for north-east Queensland are varied depending on location and influence from systems such as ENSO and the monsoon. Modelling the effects of enhanced greenhouse conditions on ENSO gives varied results with some studies indicating La Niña events will become more stable and that the recent increased frequency of El Niño events is in response to the current rise in global temperature and will not be the case in a generally warmer, stable climate (Herbert and Dixon 2003; Huber and Caballero 2003; Tsonis, Elsner *et al.* 2005). Increases in the intensity and frequency of extreme rainfall events have been modelled across Australia and found to be highest in mountainous terrain, with an average increase in rainfall intensity of between 20 and 40% by 2040 (Abbs 2004).

Climate projections for the north-east Queensland region (Whetton 2003; Whetton, McInnes *et al.* 2005) indicate that by 2030 rainfall is expected to change by -5% to +15% from December to February, and -15% to 5% for March to November (Figure 9.4) highlighting the degree of uncertainty in model projections for this region.

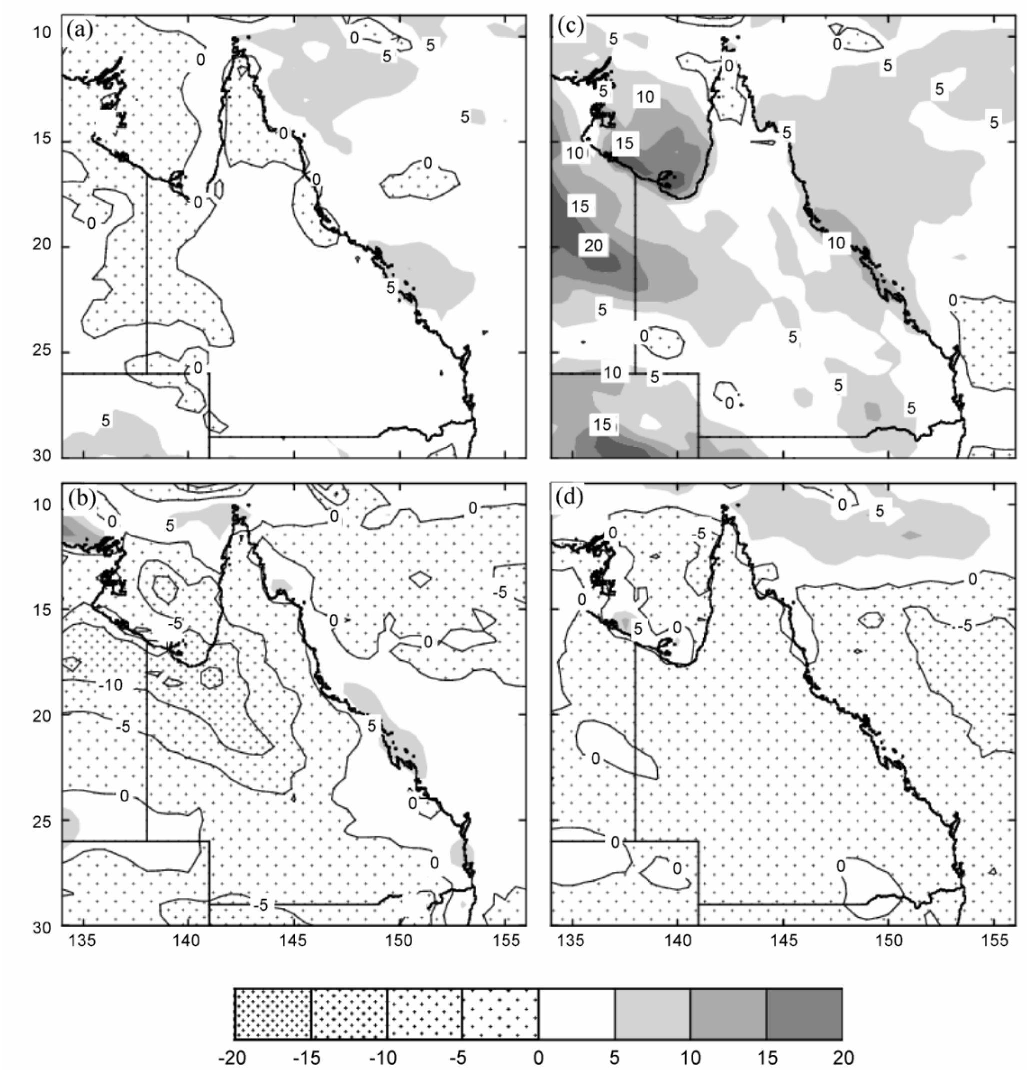


Figure 9.4 Projected percentage change of rainfall per degree of global warming for Queensland interpolated to a 1 degree grid by CSIRO DARLAM-60 regional climate model, for (a) summer (December – February), (b) winter (June – August), (c) autumn (March – May) and (d) spring (September – November) (adapted from Walsh, Hennessy *et al.* 2001).

The frequency of extreme rainfall events is expected to increase. As an example, the likely return period for an 80 mm per day extreme rainfall event in north Queensland is expected to drop from 40 years down to 20 years (IPCC 2001b; Walsh, Hennessy *et al.* 2001) (Figure 9.5). Fewer, more intense rainfall events in north-east Queensland will affect the quality and volume of freshwater in the region (Chiew, Harrold *et al.* 2003; Walsh, Cai *et al.* 2002).

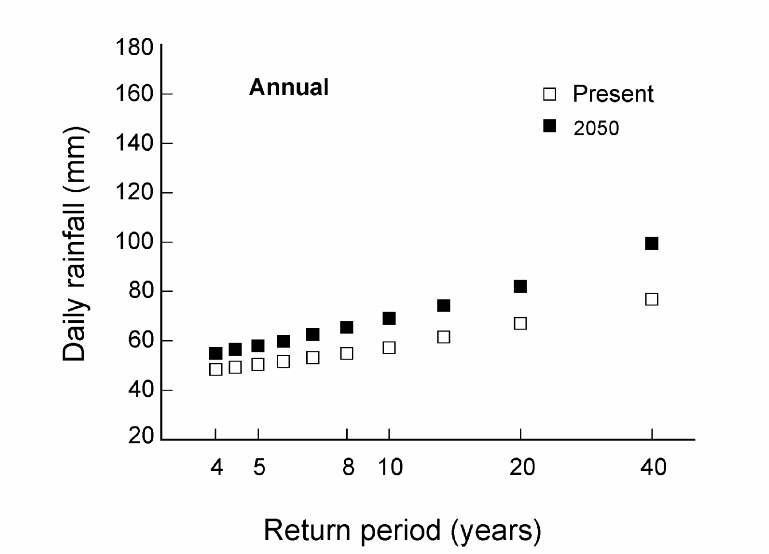


Figure 9.5 Expected return periods for extreme rainfall events for north Queensland as modelled by the CSIRO DARLAM-60 regional climate model (adapted from Walsh, Hennessy *et al.* 2001).

Evaporation

Most studies argue that increased temperatures and evaporation/evapotranspiration would lead to hotter and drier droughts even if rainfall totals remain largely unaffected (IPCC 2001b; Nicholls 2003; Risbey, Karoly *et al.* 2003; Rosenzweig and Hillel 1998). However, some researchers (e.g. Roderick and Farquhar 2004) propose that actual evaporation will decrease on average across the continent as vapour pressure increases, reducing the overall aridity of the country.

Sea levels

The projections for global sea level rise lie between 0.20 and 0.59 m by 2090 – 2099 across the range of climate scenarios (IPCC 2007). These estimates include thermal expansion from oceans and freshwater contributions from glaciers, Greenland and Antarctica, but do not include uncertainties pertaining to changes in ice sheet flow. It has been estimated that if the West Antarctic Ice Sheet were to collapse (i.e. the currently grounded ice), sea levels could be expected to rise by between four and six meters – an event that would flood extensive coastal and wetland areas around the globe (Oppenheimer 1998).

Tropical cyclones

GCM outputs of future global tropical cyclone frequency vary by ±50% (IPCC 2003), and so do not provide a clear indication of what may happen. However, recent studies (e.g. Knutson and Tuleya 2004; Walsh and Ryan 2000) have reinforced the findings that cyclones will become more intense, with an expected increase in wind speeds of 5 – 10%, peak rainfall increases of 15 – 30%, and an increase in the number of category 5 cyclones. Future tropical cyclones in the north-east Queensland region are projected to increase in maximum intensity but show little change in their region of formation or number (Walsh, Cai *et al.* 2002).

9.3 CLIMATE CHANGE AND PRINCESS CHARLOTTE BAY

Temperature

In the Princess Charlotte Bay area, instrument measurements of maximum and minimum temperature are recorded at Coen Post Office (1953 – 1972) and Coen Airport (1968 – current), Musgrave (1990 – current), Cooktown Post Office (1957 – 1987) and Cooktown Mission Strip (1988 – current). Recent measurements for each variable at Coen Airport and Cooktown Mission Strip were extracted from the SILO patch point data set (http://www.bom.gov.au/silo) and plotted (Figure 9.6).

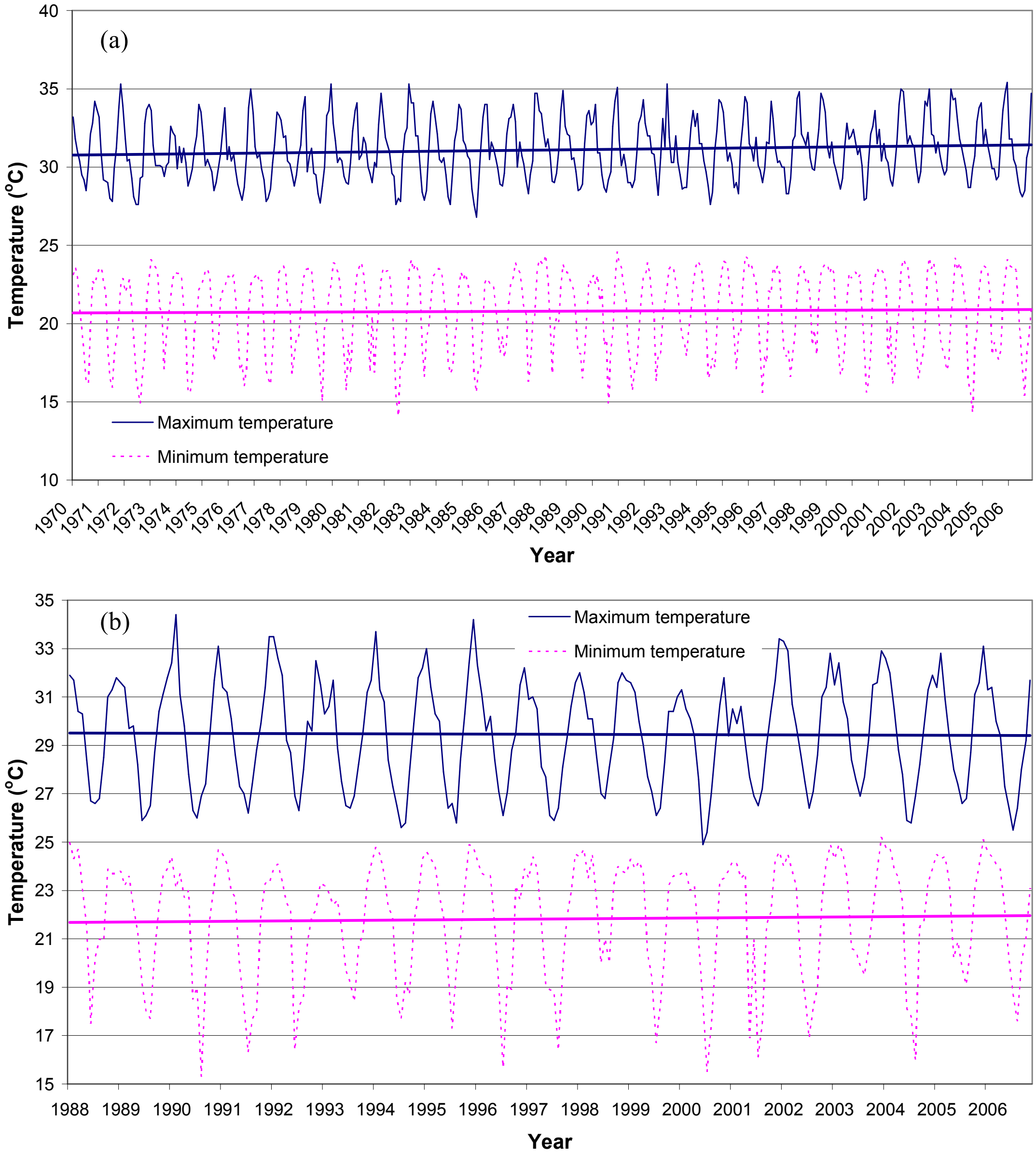


Figure 9.6 Monthly instrument recordings of maximum and minimum temperature for a) Coen Airport (1970 – 2006) and b) Cooktown Mission Strip (1988 – current) (SILO patched point database). Straight lines represent the long-term trend for each variable. Note differences in the Y-axis.

Rainfall

Annual rainfall at both of the rainfall recording stations in the study area (Musgrave Station on the northern edge and Laura Station in the south) has increased since the beginning of the century, but decreased in the past 30 years, most likely a distortion from the anomalously wet 1970s (Figure 9.7).

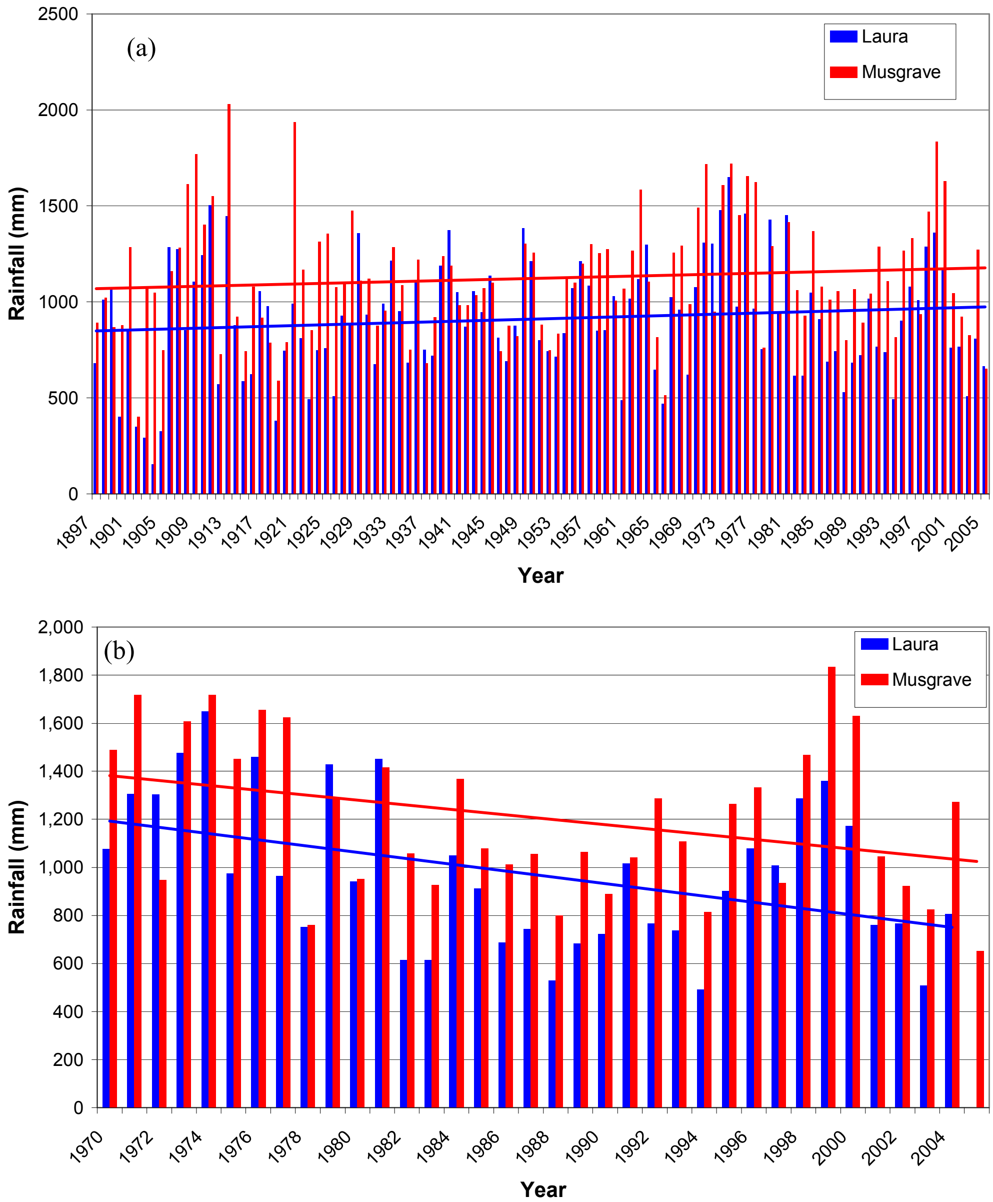


Figure 9.7 Annual rainfall at Musgrave and Laura stations in the Princess Charlotte Bay study area for (a) 1897 – 2005 and (b) 1970 – 2004 (Australian Rainman database). Straight lines represent the long-term trend.

Evaporation

Only two climate stations in the area have recorded evaporation in recent years – Coen Airport 1975 – current) and Cooktown Mission strip (1988 – current). Both show a marginal increase in evaporation over the period of records (Figure 9.8).

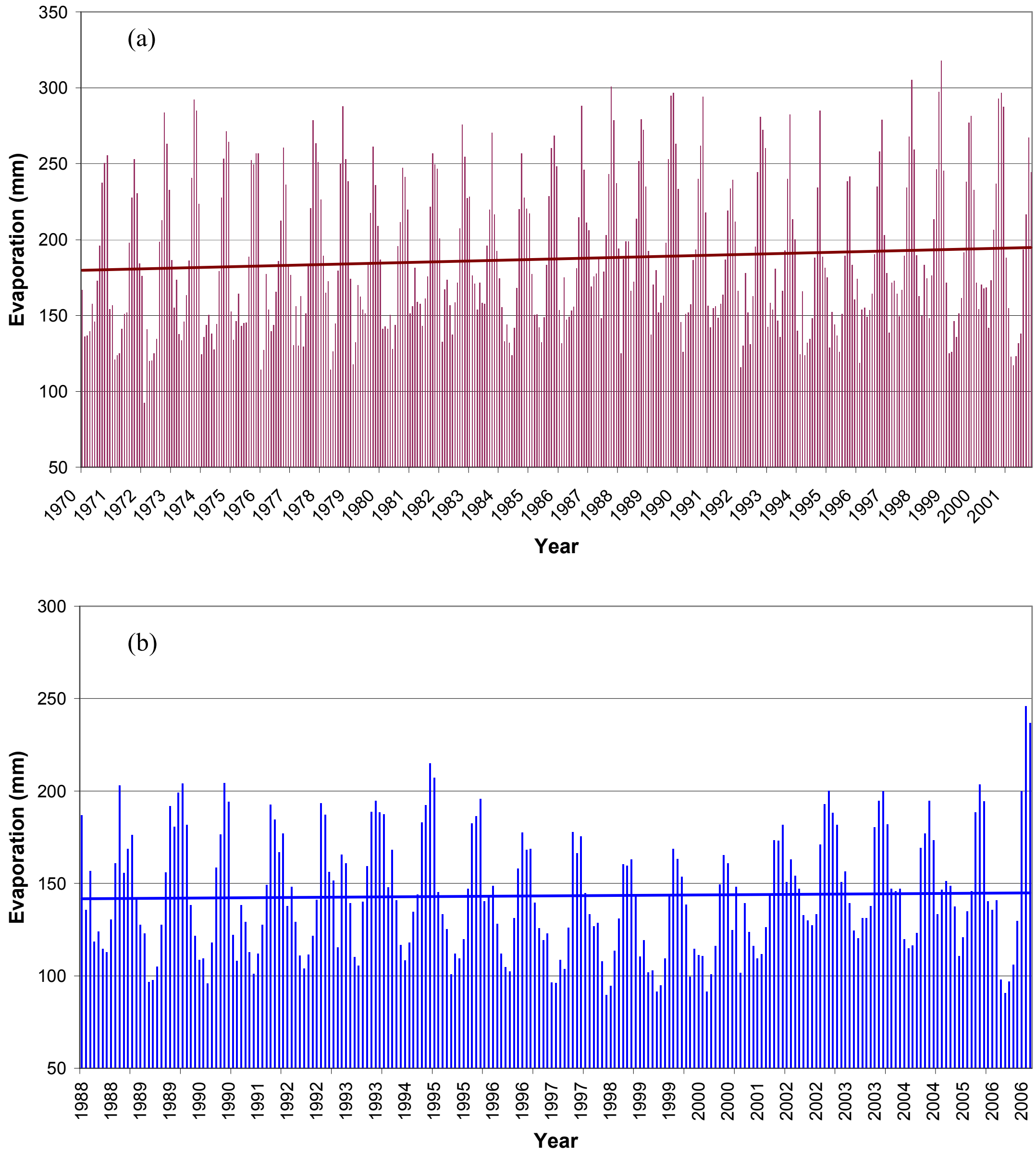


Figure 9.8 Monthly recorded Class A pan evaporation for the Princess Charlotte Bay area at a) Coen Airport (1975 – 2006) and b) Cooktown Mission Strip (1988 – 2006) (SILO patched point database). The straight line for each location represents the long-term trend.

Wind

To determine recent trends in wind, monthly wind data (mean monthly V-wind (meridional – north/south) and U-wind (zonal – east/west)) were extracted for a point in Princess Charlotte Bay (114^{o}E 14^{o}S) from the NCEP/NCAR Reanalysis Data: Derived Products data request web page at the NOAA Climate Diagnostics Centre. (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.derived.html#surface). Data is at sea level for a 2.5° latitude x 2.5° longitude grid. Data show a slight decrease in U-wind speed and slight increase in V-wind components from 1980 – 2004 (Figure 9.9).

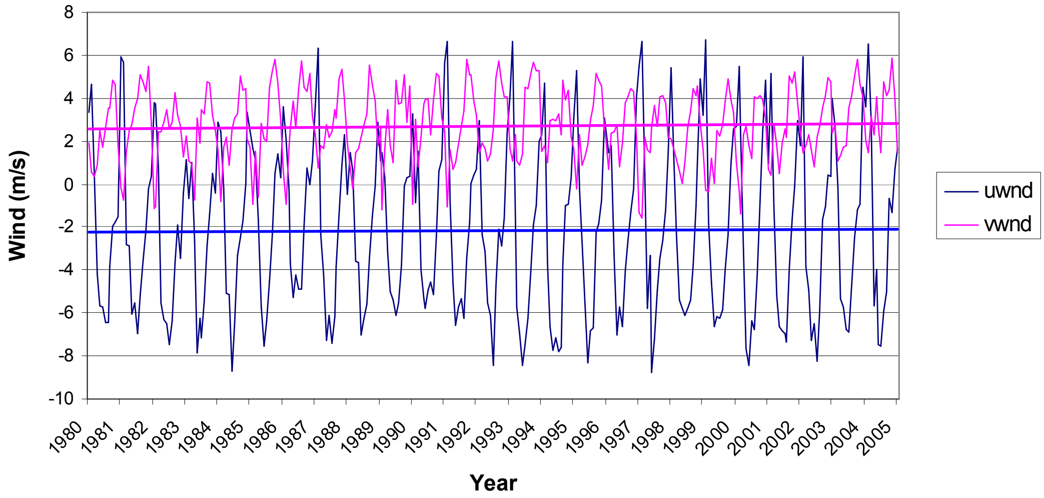


Figure 9.9 Monthly V-wind and U-wind vectors for Princess Charlotte Bay (1980 – 2005) (NCEP/NCAR Reanalysis Data). The straight lines represent the long-term trend in each.

Tropical cyclones

Tropical cyclones affect Princess Charlotte Bay on a regular basis and range in intensity and the degree of damage incurred (see Chapter 6 for details). A prehistoric record of cyclone activity in Princess Charlotte Bay was determined by Nott and Hayne (2001) through the analysis of coral rubble ridge sequences along the shore. Results indicated that the frequency of cyclones over the past 3000 – 5000 years has remained relatively unchanged (an intense category 4 or 5 cyclone approximately every 177 years). However, a centennial scale cycle in the record suggests that the current century has been a period of quiescence relative to other periods in history. How often such intense cyclones will form in the region in the future is still uncertain, although, a number of studies (e.g. Walsh and Ryan 2000) expect them to become marginally more frequent as cyclone intensities increase.

9.4 IMPACT OF CLIMATE CHANGE ON FISHERIES

Results from the modelling of global ocean ecosystems in a warmer climate indicate a contraction of the highly productive marginal sea-ice biomes, expansion of the low productivity tropical biomes, and an increase in vertical stratification of the oceans (Sarmiento, Slater *et al.* 2004). Australian ecosystems are considered particularly vulnerable to climate change due to possible changes in the frequency of El Niño events, rainfall along the east coast, and increases in cyclone and rainfall intensity. Ecosystems highlighted as most at risk include coral reefs (IPCC 2001a), mangroves and coastal wetlands (used by many species including barramundi as nursery habitats), and the World Heritage reef and rainforest areas in north-east Queensland (ACG 2005).

Climate change could be expected to affect both the commercial and recreational fisheries of Australia as aquatic ecosystems are influenced by changes to freshwater flows, water temperature, wind, nutrient and salinity levels (Frye 1983). Changes to wind regimes will likely drive changes in ocean currents and water temperature, affecting areas of upwelling and associated primary production, nutrient transfer and salinity. These changes will in turn impact on the spawning and transport of larvae and juvenile fish, adult migrations, growth rates, food supplies and perhaps even predator/prey relationships for certain species (Frye 1983; Kapetsky 2000; Putten and Rassam 2001). Short lived species such as the banana prawn currently show large inter-annual variations in catch and are expected to be highly sensitive to even small perturbations in the environment (Williams 2002).

Freshwater and estuarine fisheries (such as the barramundi) that rely on freshwater flows to bring nutrients and provide other services to the ecosystem, may be affected by increased water temperatures, changes to flow regimes, and an increase in the number or duration of drought events (Frye 1983; Kapetsky 2000). Such changes have already been reported in the Tejo River estuary in Portugal (Europe's largest estuary) where rising water temperature has resulted in a dramatic change in the species of fish (Cabrala, Vasconcelosa *et al.* 2007). Sea level rise and heightened storm surges will also have a significant impact on coastal belt habitats and communities (IPCC 2001a). Sections of the north-east Queensland coastal belt, and in particular wetland and mangrove ecosystems, are at high risk from sea level rise and flooding due to the low elevation and number of large rivers (Crimp, Balston *et al.* 2003). In the past, mangroves have moved inland in response to rising sea levels. However, constraints in the form of urbanisation and farming will limit this migration in the future, reducing available habitat (Woodroffe 1993).

Although a number of studies have been undertaken to examine the likely impacts of climate change on coral reefs (including the Great Barrier Reef) (e.g. Done, Whetton *et al.* 2003), none have specifically considered the impacts of climate change on inshore fin-fish in the Australian region. Publications to date that have linked Australian fisheries and climate change have been based on the studies of climate variability and fisheries reviewed here (e.g. Hobday and Matear 2006; Meynecke, Lee *et al.* 2006).

9.5 DATA

The baseline data used to model future Princess Charlotte Bay barramundi catch was that used in the short-term analyses and predictive model development (1989/90 – 2001/02). All climate change scenarios use this data set as a basis, and results are compared to the baseline climate. Baseline data for the global climate model (GCM) runs in OZCLIM represent a climate centred on the year 1990.

9.6 METHODOLOGY

To determine the likely impacts of climate change on barramundi catch adjusted for effort (CAE) in Princess Charlotte Bay, existing baseline data were modified on the basis of a range of GCM predicted scenarios for the area. The selection of climate change scenarios was based on discussions with authors of other climate change studies, recommendations in the United Nations Environment Program (UNEP) "Handbook on methods for climate change impact assessment and adaptation strategies" (Feenstra, Burton *et al.* 1998), and a review of available data and GCM outputs for the north-east Queensland region. Scenarios chosen for analysis were assessed against the four criteria outlined in the UNEP handbook:

1. Scenarios should be consistent with the broad range of global warming projections based on increased atmospheric concentrations of greenhouse gases;
2. Scenarios should be physically plausible; that is they should not violate the basic laws of physics;
3. Scenarios should estimate a sufficient number of variables on a spatial and temporal scale that allows for the impact assessment; and

4. Scenarios should, to a reasonable extent, reflect the potential range of future regional climate change.

Of the three types of climate change scenarios (those based on outputs from GCMs, synthetic scenarios, and analogue scenarios), synthetic scenarios were selected. Synthetic scenarios (otherwise known as arbitrary scenarios) are based on incremental changes to baseline climate variables (e.g. +2^{o}C temperature, +10% rainfall) and allow for both a transparent analysis of a wide range of potential climate changes, and are easily adopted by policy makers (Feenstra, Burton *et al.* 1998). In addition, synthetic scenarios do not require large computing resources, are reasonably quick to undertake and can be easily updated with the latest GCM outputs as they become available. One disadvantage of the technique is that the spatial resolution of perturbations in climate is limited – a minimal risk given the small study area considered in this analysis. Additionally, when assessing the impacts to a system that is affected by a number of climate variables (as is the case here), there is the risk of including a scenario that is not physically plausible (Penny Whetton, Senior research Scientist, CSIRO Atmospheric Sciences Research Centre, pers. comm. December 2006).

The option of using a set of analogue years (such as El Niño/near-El Niño years) was considered risky given past and possibly future changes to the relationship between ENSO, the SOI and rainfall (Feenstra, Burton *et al.* 1998). There is current uncertainty as to future El Niño frequency (e.g. Knutson and Manabe 1997; Tsonis, Elsner *et al.* 2005), and as past El Niño events were not driven by increases in global greenhouse gases there may be changes to the way ENSO operates in the future (Feenstra, Burton *et al.* 1998).

Future climate projections for a specific location vary between GCMs, and for this reason it is accepted that climate change assessments include the range of projections from a number of models (Walsh, Hennessy *et al.* 2001). An assessment of the various GCM outputs for north-east Queensland is planned by CSIRO for early 2007 (Penny Whetton, Senior Research Scientist, CSIRO Atmospheric Sciences Research Centre, pers. comm. December 2006). In the meantime, the range of projections for seasonal temperature, rainfall, evaporation and SSTs from the CSIRO developed OZCLIM program were considered the best estimation of future climate for the Princess Charlotte

Bay area and so were used in the development of plausible, regionally and seasonally specific synthetic scenarios. GCMs included in the OZCLIM program are: CSIRO Mk2, Canadian Climate Centre CGCM1, GFDL R15-a, Hadley Centre HAD CM2, Hadley Centre HAD CM3, Max Planck EACHAM 4 / OPY C3, Max Planck EACHAM 3/LSG, CSIRO DARLAM 125 km, and NCAR DOE-PCM. Each of these models was selected for inclusion into OZCLIM on the basis of their capacity to accurately hindcast climate across Australia (Penny Whetton, Senior Research Scientist, CSIRO Atmospheric Sciences Research Centre, pers. comm. December 2006).

Three IPCC TAR Special Report on Emissions Scenarios (SRES scenarios) were run through each GCM (A1B – rapid increase in economic growth, population peaking in the mid century and a rapid shift towards a balance of fossil and non-fossil fuels, A2 – continued population and economic growth with slower technological change, and B1 – population peak mid century and a focus on environmental sustainability) for the years 2030 and 2070. A mid-range climate sensitivity was selected (2.5^{o}C for a doubling of CO^2) and, to capture the likely range of future changes, the second highest and second lowest GCM output was selected for generation of the synthetic scenarios. Outputs used were the percent change from the baseline for dry season (July – September) rainfall and annual evaporation both in the year of spawning for input into Predictive Model I developed in Chapter 8. Future climate data (synthetic scenarios) were calculated by adjusting the baseline data by the percentage change identified in the selected GCM outputs. The resulting synthetic scenario data sets were run through the barramundi Predictive Model I, outputs plotted and distributions compared to the baseline analysis using a time series and box plot. Means were tested for significant differences using an analysis of variance (ANOVA) including the year as a block effect to take out the inter-annual variability and a test for least significant difference between pairs (pairwise LSD test).

Finally, as temperature dictates the range of barramundi, a spatial analysis of the change in SST for each of the three SRES scenarios was undertaken for Australia using projections from the CSIRO REEFCLIM program. Sea surface temperatures from the CSIRO Mark 3 regional model contained in REEFCLIM in the year 2030 and 2070 were compared with current SSTs as an indication of the likely range of the species in the future.

Hypotheses

When each component of climate change is considered in tandem with the life cycle model of the barramundi, a number of potential effects on the barramundi fishery are evident:

- Increased temperatures would change ocean, estuary, stream and nursery habitats affecting egg hatch, juvenile development and adult growth rates and maturation;
- Changes to rainfall, and hence freshwater flows, are likely to alter the extent of nursery habitats and connectivity between freshwater and estuarine areas for mature males returning to spawn;
- Changes to evaporation would alter the extent and salinity of nursery habitats;
- Sea level rise has the potential to both increase brackish nursery habitats by inundating existing shallow floodplains and reduce current freshwater habitats;
- Changes to the intensity and/or frequency of extreme events including cyclones will affect numerous stages of the fish life cycle depending on the habitat affected and the timing of the events.

Each of these climate changes is likely to impact on the barramundi fishery in a different way, through a highly complex series of interactions. However, in general it was hypothesised that changes that increase freshwater and sea water temperatures, increase flow and coastal rainfall, increase sea level and reduce evaporation will result in an increase in subsequent catch.

9.7 RESULTS

The range of GCM projections for rainfall and evaporation from the OZCLIM analysis for Princess Charlotte Bay are shown in Figures 9.10 and 9.11. The two models selected for development of a synthetic scenario for dry season rainfall were the GFDL model R15-a (second highest projected increase in rainfall) and the Canadian Climate Centre model CGCM1 (second lowest projected decrease), and for annual evaporation the Canadian Climate Centre model CGCM1 (the second highest projected increase) and the NCAR model DOE-PCM (second lowest projected increase). The projected changes (percent change from baseline) for both rainfall and evaporation from these models are shown in Tables 9.1 and 9.2 (details of all calculations are in Appendix 11). The changes were applied to the baseline data set and the resulting synthetic scenario data sets (Table 9.3) were run through the Princess Charlotte Bay barramundi Predictive Model I.

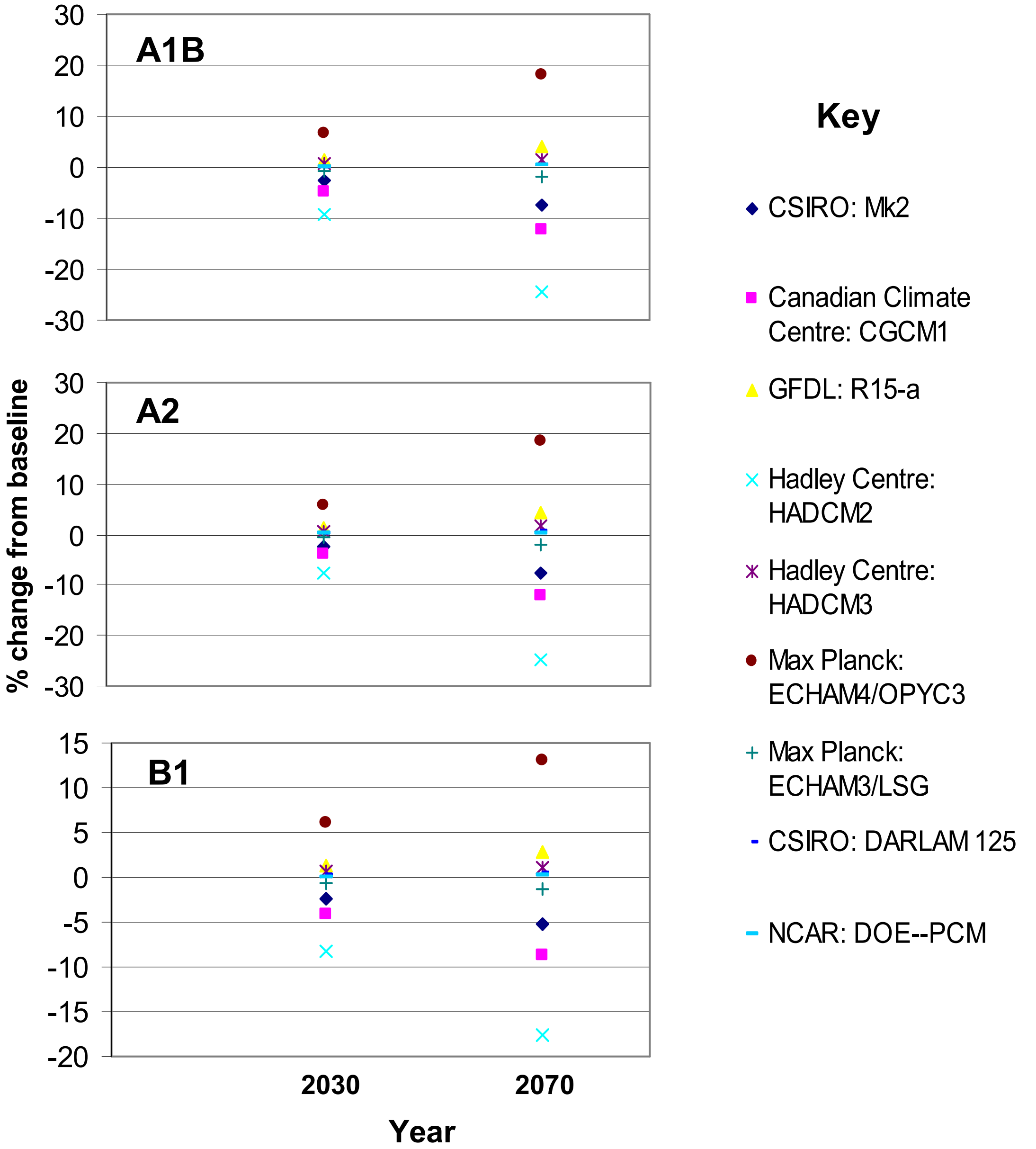


Figure 9.10 Plot of global climate model predicted changes to dry season (July – September) rainfall (%) compared to the base climatology (1990 year) for Princess Charlotte Bay area for the years 2030 and 2070 for the three SRES scenarios selected: A1B (top), A2 (middle) and B1 (bottom) (OZCLIM Version 2.0.1).

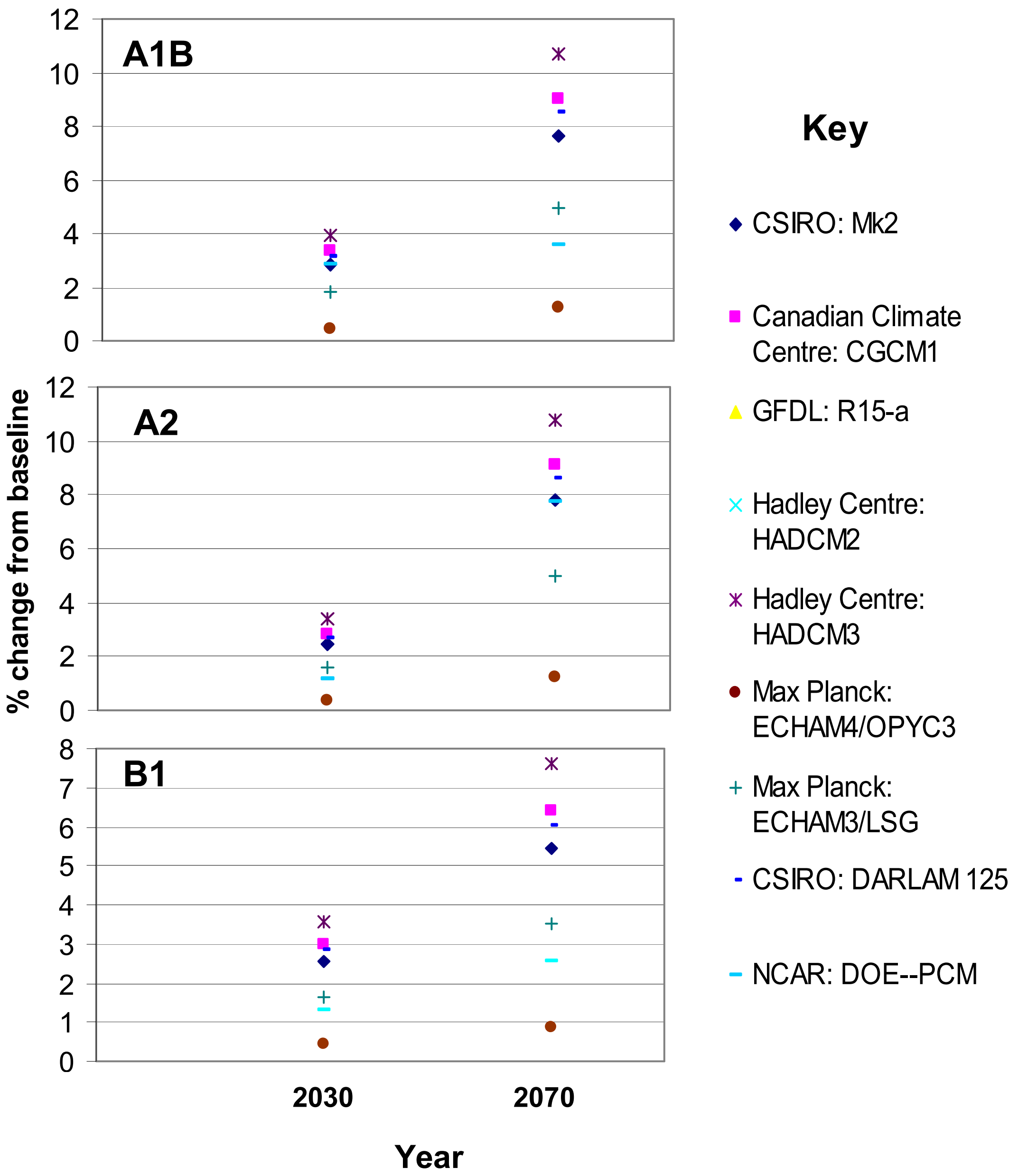


Figure 9.11 Plot of global climate model predicted changes to annual evaporation (%) compared to the base climatology (1990 year) for Princess Charlotte Bay area for the years 2030 and 2070 for the three SRES scenarios selected: A1B (top), A2 (middle) and B1 (bottom) (OZCLIM Version 2.0.1).

Table 9.1 Dry season (July – September) rainfall scenarios generated to determine impacts of climate change on the barramundi fishery of Princess Charlotte Bay. Values represent the likely range of rainfall changes (second highest to second lowest) as generated by a selection of global climate models in the OZCLIM program for each of three SRES initiating scenarios (A1B, A2 and B1) for the years 2030 and 2070.

Scenario	Source	Rainfall change (%) 2030	2070
High A1B rainfall	GFDL: R15-a	+1.48	+4.02
Low A1B rainfall	CCC: CGCM1	-4.67	-12.12
High A2 rainfall	GFDL: R15-a	+1.28	+4.16
Low A2 rainfall	CCC: CGCM1	-3.85	-12.28
High B1 rainfall	GFDL: R15-a	+1.34	+2.86
Low B1 rainfall	CCC: CGCM1	-4.06	-8.64

Table 9.2 Evaporation scenarios generated to determine possible impacts of climate change on the barramundi fishery of Princess Charlotte Bay. Values represent the likely range of evaporation changes (second highest to second lowest) as generated by a selection of global climate models in the OZCLIM program for each of three initiating SRES scenarios (A1B, A2 and B1) for the years 2030 and 2070.

Scenario	Source	Evaporation change (%) 2030	2070
High A1B evaporation	CCC: CGCM1	+3.32	+8.99
Low A1B evaporation	NCAR: DOE-PCM	+2.83	+3.58
High A2 evaporation	CCC: CGCM1	+2.85	+9.11
Low A2 evaporation	NCAR: DOE-PCM	+1.14	+7.75
High B1 evaporation	CCC: CGCM1	+3.01	+6.41
Low B1 evaporation	NCAR: DOE-PCM	+1.28	+2.55

Outputs from the Princess Charlotte Bay barramundi Predictive Model I run using the synthetic scenarios generated are detailed in Appendix 11 and summarised using both a time-series plot (Figure 9.12) and a box plot (Figure 9.13). The statistical difference between scenarios was examined using an ANOVA and pairwise LSD ANOVA. The ANOVA showed that at least two of the scenarios were significantly different and so a pairwise LSD ANOVA was used to rank means for each scenario (Table 9.4). As the residuals from the analysis were slightly non-normal, the results were re-examined using the non-parametric Friedman's test which returned near identical results.

Table 9.3 Each of the synthetic climate change scenarios entered into the Princess Charlotte Bay barramundi Predictive Model I developed in Chapter 8. Scenarios were generated by a selection of global climate models in the OZCLIM program for each of three initiating SRES scenarios (A1B, A2 and B1) for the years 2030 and 2070.

Scenario	Source
Baseline	Current climate (1987/1988 – 1999/2000)
A	A1B scenario using CCC rainfall and CCC evaporation for 2030
B	A1B scenario using CCC rainfall and CCC evaporation for 2070
C	A2 scenario using CCC rainfall and CCC evaporation for 2030
D	A2 scenario using CCC rainfall and CCC evaporation for 2070
E	B1 scenario using CCC rainfall and CCC evaporation for 2030
F	B1 scenario using CCC rainfall and CCC evaporation for 2070
G	A1B scenario using GFDL rainfall and NCAR evaporation for 2030
H	A1B scenario using GFDL rainfall and NCAR evaporation for 2070
I	A2 scenario using GFDL rainfall and NCAR evaporation for 2030
J	A2 scenario using GFDL rainfall and NCAR evaporation for 2070
K	B1 scenario using GFDL rainfall and NCAR evaporation for 2030
L	B1 scenario using GFDL rainfall and NCAR evaporation for 2070

Baseline monthly average SSTs for the Australian region was mapped using the CSIRO REEFCLIM program (Figure 9.14). In Australia, the current range of the barramundi is from the Mary River on the east coast (26^{o}30’S) to the Ashburton River on the west coast (22 ^{o}30’S). Average monthly SSTs for each location in the year 1995 (baseline year) was 24.40^{o}C and 24.73^{o}C respectively (an average of 24.56^{o}C). Each of the three initiating SRES scenarios (A1B, A2 and B1) were run for the CSIRO Mark 3 regional model for the years 2030 and 2070 for a mid range sensitivity (as for the synthetic climate scenarios). The potential change to the barramundi distribution is marked on the map as the latitude where the average temperature of 24.56^{o}C occurred for each year modelled. By the year 2070, SSTs will be warm enough for barramundi colonisation as far south as Newcastle on the east coast and Geraldton on the west coast, depending on the availability of suitable habitat, and assuming the current average minimum temperature threshold is maintained – a southerly shift of up to 800 kilometres from present day.

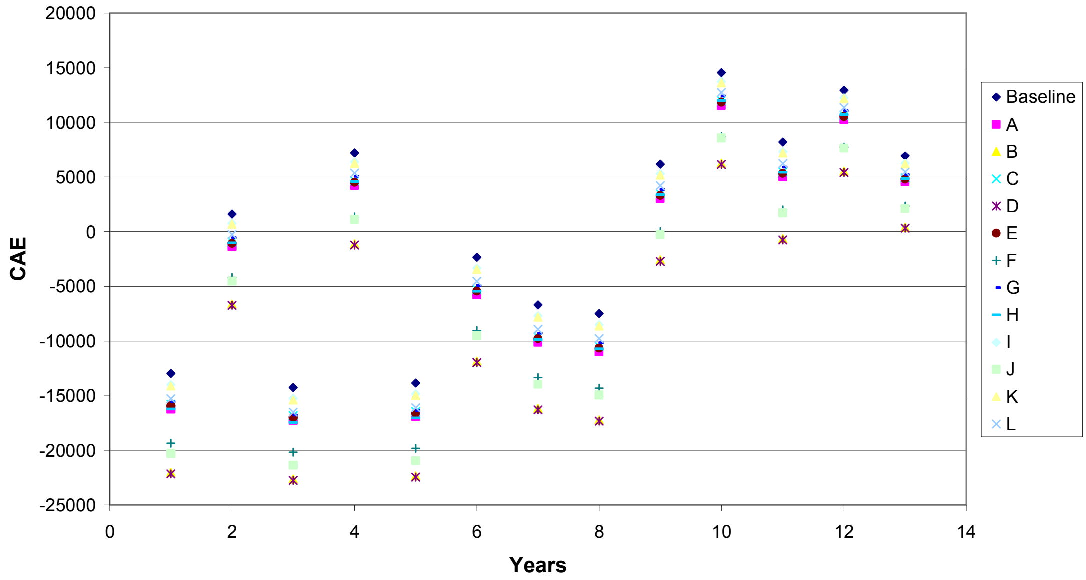


Figure 9.12 Plot of predicted Princess Charlotte Bay barramundi catch adjusted for effort (CAE) for the suite of climate change scenario years outlined in Table 9.4 Results are compared to the baseline catch predictions (1989/90 – 2001/02).

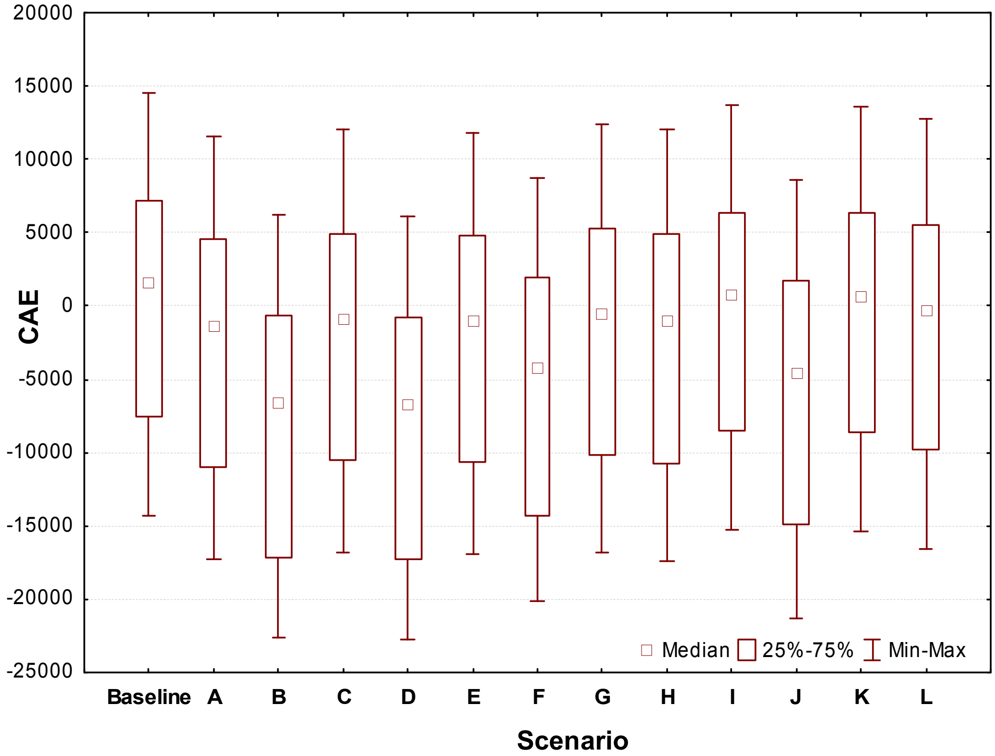


Figure 9.13 Box plot showing the distribution of predicted Princess Charlotte Bay barramundi catch adjusted for effort (CAE) for the suite of climate change scenarios outlined in Table 9.4.

Table 9.4 A comparative table of results from the pairwise LSD ANOVA analysis (with year as a blocking effect) and the non-parametric Friedman test, each for the projected barramundi catch adjusted for effort (CAE) for the suite of synthetic climate change scenarios outlined in Table 9.4. For the ANOVA, means with the same subscript are not significantly different at the $p < 0.05$ level.

Analysis of Variance		Friedman	
Scenario	Mean CAE	Rank	Scenario
D	-8654 a	1	D
B	-8535 a	2	B
J	-6505 b	3	J
F	-6009 c	4	F
A	-3076 d	5	A
H	-2830 e	6	E/H
E	-2775 e	7	E/H
C	-2626 e	8	C
G	-2319 f	9	G
L	-2005 g	10	L
K	-1004 h	11	K
I	-889 h	12	I
Current	0 i	13	Current

Results from the pairwise LSD ANOVA show that all of the future synthetic climate change scenarios tested predict a mean barramundi CAE for Princess Charlotte Bay that is significantly less than the current mean. Scenarios D (A2 SRES scenario using CCC rainfall and CCC evaporation for 2070) and B (A1B SRES scenario using CCC rainfall and CCC evaporation for 2070) are not significantly different from each other but represent the most significant decrease in barramundi catch from the current baseline. These are followed in descending difference from the current mean by scenario J (A2 SRES scenario using GFDL rainfall and NCAR evaporation for 2070), which is significantly different from F (B1 SRES scenario using CCC rainfall and CCC evaporation for 2070), significantly different from A (A1B SRES scenario using CCC rainfall and CCC evaporation for 2030), significantly different from H (A1B SRES scenario using GFDL rainfall and NCAR evaporation for 2070), E (B1 SRES scenario using CCC rainfall and CCC evaporation for 2030) and C (A2 SRES scenario using CCC rainfall and CCC evaporation for 2030), significantly different from G (A1B SRES scenario using GFDL rainfall and NCAR evaporation for 2030), significantly different from L (B1 SRES scenario using GFDL rainfall and NCAR evaporation for 2070) significantly different from K (B1 SRES scenario using GFDL rainfall and NCAR evaporation for 2030) and I (A2 SRES scenario using GFDL rainfall and NCAR evaporation for 2030).

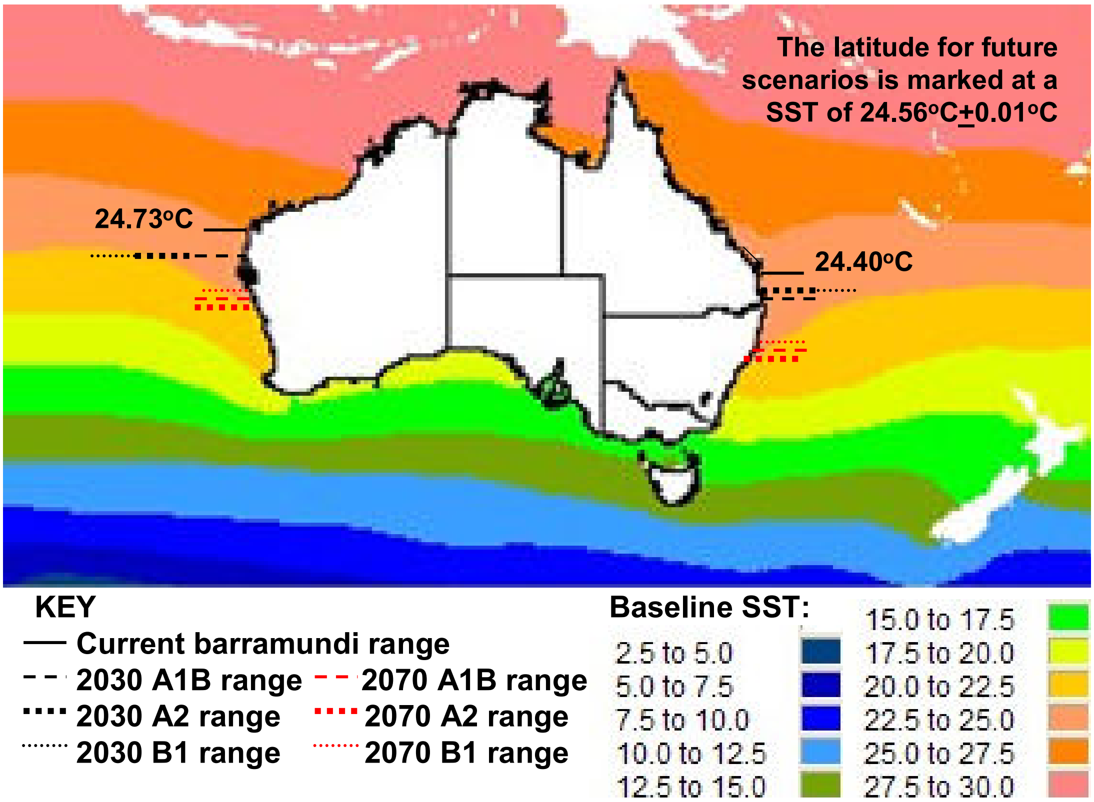


Figure 9.14 Map of Australian sea surface temperatures (SST) generated by the CSIRO REEFCLIM program for the baseline year of 1995. The change in potential distribution of the barramundi is marked for the three initiating scenarios (A1B, A2 and B1) for the year 2030 and 2070 at the current average minimum temperature threshold for the species of 24.56°±0.01°C.

9.8 DISCUSSION

The projected changes in climate most likely for north-east Queensland (including the Princess Charlotte Bay area) as a result of anthropogenic global warming include an increase in temperature (both terrestrial and SSTs), increase in evaporation, changes to rainfall as a result of changes to the frequency of El Niño events, an increase in the frequency of extreme events, sea level rise, and an increase in tropical cyclone intensity (Abbs 2004; Herbert and Dixon 2003; Huber and Caballero 2003; IPCC 2001b; Knutson and Tuleya 2004; Nicholls 2003; Walsh, Cai *et al.* 2002; Walsh, Hennessy *et al.* 2001; Whetton 2003). Each of these changes could be expected to affect fisheries in the region including the barramundi (Crimp, Balston *et al.* 2003; Frye 1983; Meynecke, Lee *et al.* 2006).

For barramundi, access to freshwater habitats is essential for survival and recruitment. Individuals are not found in areas without permanently flowing rivers (Dunstan 1959) and so a future reduction in freshwater flow as a result of climate change may well reduce the distribution, recruitment success and catchability of the species. In the Princess Charlotte Bay area, projections for changes to rainfall vary from -5% to +15% (Walsh, Cai *et al.* 2002), although, increases in rainfall are likely to come in the form of extreme events. The results from Chapters 4 and 6 confirmed that climate variables that were significantly correlated with barramundi CAE in Princess Charlotte Bay each described a condition that would result in extensive and conducive nursery habitat for young-of-year barramundi survival: high wet season rainfall and freshwater flows, high dry season rainfall, warm wet season SSTs and low annual/wet season evaporation all two years prior to catch. Significant correlations between CAE and both rainfall and freshwater flow in the pre-wet and wet seasons (October – March) in the year of catch confirmed the hypothesis that mature males are flushed into the commercial fishery at the beginning of the wet season as increased rainfall and freshwater flows improve connectivity between freshwater habitats and the ocean. Apart from the linear correlations, pre-wet season (October – December) rainfall and early dry season (April – June) freshwater flow two years prior to catch had a quadratic relationship with barramundi CAE, peaking at 325 mm and 250 000 Ml, respectively, beyond which CAE declined, either because of a direct detrimental impact on the fish or a change in the ecosystem that somehow reduced survival. Projected increases in the number of intense tropical cyclones, and extreme rainfall and flow events, would in this case be expected to reduce recruitment success in the Princess Charlotte Bay fishery. Non-linear relationships for other barramundi populations along the coast of Australia are likely to be different, depending on the physical attributes of the catchment, river and estuarine habitats and response from the fishery.

The variables in the barramundi Predictive Model 1 used to quantify the impacts of climate change on the Princess Charlotte Bay barramundi population were dry season (July – September) rainfall and annual evaporation. Evaporation was interpolated Class A pan evaporation (i.e. potential evaporation (*Ep*)), which is approximately 0.7 lake evaporation (*Eo*) (Linacre 2004). For the shallow wetland habitats of Princess Charlotte Bay, estimates of future *Ep* is considered to be a realistic projection of expected changes to *Eo*, although actual values of lake evaporation would be 1.4 times higher than *Ep* as per the relationship. Most GCM projections for the north-east coast of Queensland indicate an increase in future *Ep*, in response to more El Niño events and an increase in drought conditions – a trend that has been seen in Australia over the past ten years, and in the Princess Charlotte Bay area since the 1970s (Figure 9.7) (Graham Farquhar, Australian National University, pers. comm. December 2006; Mark Howden, CSIRO Atmospheric Research, pers. comm. December 2006). However, at this stage GCMs do not predict ENSO accurately (IPCC 2001b) and changes to wind speed, temperature and vapour pressure will all affect evaporation rates in the future, possibly offsetting the increases currently calculated.

Tidal inundation as a result of sea level rise may offset to some degree any reduction in freshwater wetland habitat. Barramundi populations elsewhere (e.g. those in the Fitzroy River area) are not as dependant on freshwater wetland habitats as the Princess Charlotte Bay population, and instead inhabit areas that are tidally inundated (Ian Halliday, Fisheries Research Scientist, Department of Primary Industries & Fisheries, pers. comm. November 2006). However, an analysis of the impacts of climate change on the wetlands of the Kakadu National Park, NT, indicated that the expected changes to sea level, seasonal rainfall and temperature are likely to be catastrophic and change animal populations – in particular the distribution of birds and fish species in freshwater wetlands (Finlayson 2003), a possible scenario for Princess Charlotte Bay.

A limited number of overseas studies have considered the likely changes to freshwater and wetland habitat in response to climate change. Obviously, in each case the projections are dependant on the projected local changes in climate. In south-eastern USA and Mexico (a subtropical area with a distinct summer wet and winter dry season like that of north-east Queensland), expected impacts include: increased rates of primary production, organic matter decomposition and nutrient cycling due to increased temperatures, a reduction in water quality due to decreased flows and changes in the timing and strength of freshwater flows, shorter periods of freshwater inundation, an expansion of subtropical species poleward, and altered levels of dissolved oxygen and salt (Mulholland, Best *et al.* 1997). For trout in Appalachian streams, increased temperature resulted in increased abundances of brook (*Salvelinus fontinalis*) and rainbow trout (*Oncorhynchus mykiss*), although, when combined with changes in water flow there was no clear pattern of increase or decrease. The addition of an episodic flood, however, resulted in a net loss due to the mortality of eggs and fry (Clark, Rose *et al.* 2000).

Calculations of future barramundi CAE using Predictive Model I for the synthetic climate change scenarios tested show a reduction in future catch in all cases. This is a result of increased annual evaporation, despite an increase in dry season rainfall in some scenarios. The greatest reduction in mean CAE is for scenario D (the A2 scenario using the CCC predictions for rainfall and evaporation) in the year 2070. The A2 scenario describes a future climate that is driven by continued population growth and slow technological change from current fossil fuel usage – a business as usual scenario. Annual evaporation is projected to increase (+9.11%) and rainfall is projected to decrease (-12.28%). The projected mean CAE for this scenario is -8654. This figure translates to a real reduction in catch of approximately 1000 kg from the average baseline barramundi catch (1989/90 – 2001/02). The projected mean CAE for scenario D was not significantly different from scenario B (A1B scenario using CCC rainfall and CCC evaporation for 2070), a future of rapid economic growth and a population that peaks in the mid century with a rapid shift towards a balance of fossil and non-fossil fuels. The remaining scenarios illustrate a likely range of future barramundi CAE for Princess Charlotte Bay depending on future greenhouse gas emissions and climate responses.

Obviously, changes to other climate parameters will have an impact on future barramundi catch but are not quantified in this analysis. Wet season (January – March) SSTs were identified in Chapter 4 as significantly and positively correlated with CAE two years prior to catch. Barramundi currently inhabit tropical areas to the north of Australia including Papua New Guinea and Indonesia where SSTs exceed those recorded across northern Australia (currently the average December temperature off the coast of Darwin is approximately 30^{o}C) (CSIRO 2006a). Individual barramundi have been recorded in water as high as 39^{o}C (Davis 1988), and so it is unlikely that an increase in SSTs of up to 3^{o}C (the current mid-range projection for global temperature increase (IPCC 2001b)) would affect the north-east Queensland barramundi population. However, some habitats (particularly shallow wetlands) may increase in temperature by more than 3^{o}C, posing an as yet unquantified threat to the survival of eggs, larvae and fingerlings that are less tolerant of high water temperature than adults (Russell and

Garrett 1985). An increase in SSTs southward along the coast would be expected to extend the current range of the barramundi. The analysis of future SSTs for the three SRES scenarios tested indicated that the current minimum temperature threshold that defines the existing southerly extent of the species (approximately 24.6^{o}C) will have moved poleward to Tweed Heads on the east coast, and Carnarvon on the west coast, by the year 2030 (Figure 9.14). By this stage, there is minimal difference between scenarios. However, by the year 2070 the difference in scenarios is more pronounced. Under the B1 scenario, the southern extent of the barramundi range could be expected to move south in latitude to Nambucca Heads (just south of Coffs Harbour) on the east coast and to the north of Kalbarri in the west. However, for the A2 scenario the southern range of the barramundi could extend to Newcastle in the east and Geraldton in the west – a southerly shift in range of up to 800 km compared to present. Whether barramundi actually migrate to these higher latitudes would depend on the presence of predators along the coast that normally prevent long-distance migrations (Shaklee, Salini *et al.* 1993), and the availability of freshwater outflow and other suitable habitats (that may in turn be affected by changes such as sea level rise). However, if such an aggressive predator species were to colonise these southern areas it would add pressure to existing ecosystems and the current predator/prey balance. In addition, the lucrative recreational fishing and tourist industries supported by barramundi game fishing in the north may be diffused.

As fish do not have the capacity to regulate their body heat, the potential impacts to fisheries from climate change world-wide are likely to be immense (Wood 1997). Changes in the distribution of fish species similar to those indicated by this study have already been measured overseas. An analysis of bottom trawl surveys of the north-west Atlantic Ocean from 1967 – 1993 showed changes in the mean latitude of occurrence for 12 of the 36 species collected. In addition, the weighted mean catch of pelagic species such as Atlantic mackerel and herring shifted poleward by 0.5 – 0.8 degrees of latitude for every 1^{o}C increase in average water temperature over the period of data (Murawski 1993). In the North Sea too, the distribution of both exploited and non-exploited fish species moved either in mean latitude or depth over the 25 years of available data (1977 – 2001). Fifteen species moved northward to cooler waters, in some cases a shift in mean distribution of up to 403 km and change in the boundary range of 119 km to 816 km. Most of these species, and a further six, also showed a shift in depth to pockets of deeper, colder water (Perry, Low *et al.* 2005). A similar analysis of the impacts of climate change on freshwater lake species in eastern Canada predicted a substantial redistribution of fishery yields in response to an increase in temperature of 2.5^{o}C to 7.7^{o}C as currently productive areas become marginal, and areas outside the current range for each species become optimal (Minns and Moore 1992).

Apart from changes to temperature, rainfall, and freshwater flow, there are a number of other complexities that climate change will bring to the barramundi fishery, both in Princess Charlotte Bay and further a field, for which a detailed examination are beyond the scope of this study. Sea level rise has the capacity to inundate extensive areas of freshwater habitat in Princess Charlotte Bay, which is low in elevation. If recent rates of sea level rise continue (~3 mm.yr^{-1}), levels will be ~30 cm higher by the end of the century. Other areas such as the Fitzroy River estuary that are currently tidal will be extended spatially, although, the water will obviously be deeper and not necessarily suitable as nursery habitats due to increased access from predators. Impacts to the barramundi from other higher order influences such as variability in primary productivity and changes in predator pressure at the ecological level are, at this stage, too complex to predict.

Finally, a note of caution when interpreting these results. Due to the large degree of uncertainties regarding future greenhouse gas emissions and resulting changes in the climate (including changes to ENSO, cloud cover, evaporation and wind) and the complex interactions of ecological systems, the projected changes to future barramundi catch in Princess Charlotte Bay presented here can only be considered to be a likely representation of possible future scenarios. Variables that had the greatest impact on catch over the period of the analysis because of a high degree of variability may not have as much impact in the future if climatic conditions are less variable. In contrast, climate variables that currently have a low degree of inter-annual variability may result in significant changes to the barramundi fishery if there is a relatively large shift in the mean. Additionally, extrapolating a regression model beyond the variable range that developed the model is risky, as future responses from the fishery may not be linear (as shown in Chapter 6). Non-linearity is a problem for all correlative/regression models of future impacts from climate change as obviously there is no data to validate the results of predictive models for conditions that the ecosystem has not experienced. Actual responses may be qualitatively and quantitatively different to those expected, particularly if a currently unknown threshold is exceeded.

9.9 CONCLUSION

A suite of synthetic climate change scenarios as predicted by a selection of global climate models contained in OZCLIM were run through the barramundi Predictive Model I developed in Chapter 8 to determine the likely change in future catch of the species in Princess Charlotte Bay. Results indicate that for all the future synthetic climate scenarios tested for the year 2030 and 2070, barramundi catch is likely to decrease. This is due to the projected increase in evaporation for the region and subsequent drying of shallow wetland nursery habitats, despite an increase in dry season rainfall for some scenarios. Barramundi populations that do not currently depend on wetland habitats for early life cycle survival (i.e. those that use comparable tidal habitat areas), are not likely to be affected to the same extent.

An analysis of the future distribution of the species indicates that for the current minimum temperature threshold of approximately 24.6°C, habitats as far south as Newcastle on the east coast, and Geraldton on the west coast, would be warm enough by the year 2070 for barramundi colonisation, assuming availability of suitable habitats – a southerly shift of up to 800 km. Other changes such as sea level rise will alter existing habitats and have currently unknown impacts on the ecological balance in many areas.

CHAPTER 10: SYNTHESIS, RECOMMENDATIONS AND CONCLUSIONS

10.1 INTRODUCTION

The catch of wild barramundi in north-east Australia has varied significantly from year-to-year despite rigid management of the fishery including set quotas, fishing areas and closed seasons and has not been well understood. As outlined in earlier chapters of this thesis, the analyses of climate impacts on the fishery as a driver of this variability have, to date, been limited. In addition, the results have varied both temporally and spatially depending on the timing and scale of the study. This study has examined the impacts of climate variability at both short-term (intra-annual) and long-term (inter-annual) time scales, extreme and threshold climate events and anthropogenic changes to the ecosystem. A regression model to predict future barramundi catch using only climate variables was developed and the impacts of likely anthropogenic climate change quantified by running a suite of synthetic climate change scenarios through the model. This chapter reviews the key results of the study and considers the implications for the management of the fishery.

10.2 KEY RESULTS FROM THIS RESEARCH

The climate of north-east Queensland

An understanding of which climate variables significantly influence the barramundi fishery of north-east Queensland provides the opportunity to either manage the fishery in response to the climate or manage the environmental variable (in the case of freshwater flows or availability of wetland habitat). The climate of Queensland is one of the most variable on earth: a result of influences from a number of mechanisms including, at the intra-annual scale, the seasons, monsoon and Madden Julian Oscillation (MJO), El Niño Southern Oscillation (ENSO), and at longer time-scales the Interdecadal Pacific Oscillation (IPO), Latitude of the Sub-tropical Ridge (LSTR), Southern Annual Mode (SAM) and Quasi-biennial Oscillation (QBO). The varied effects from each of these mechanisms will ensure that no two years are climatically identical (Figure 10.1).

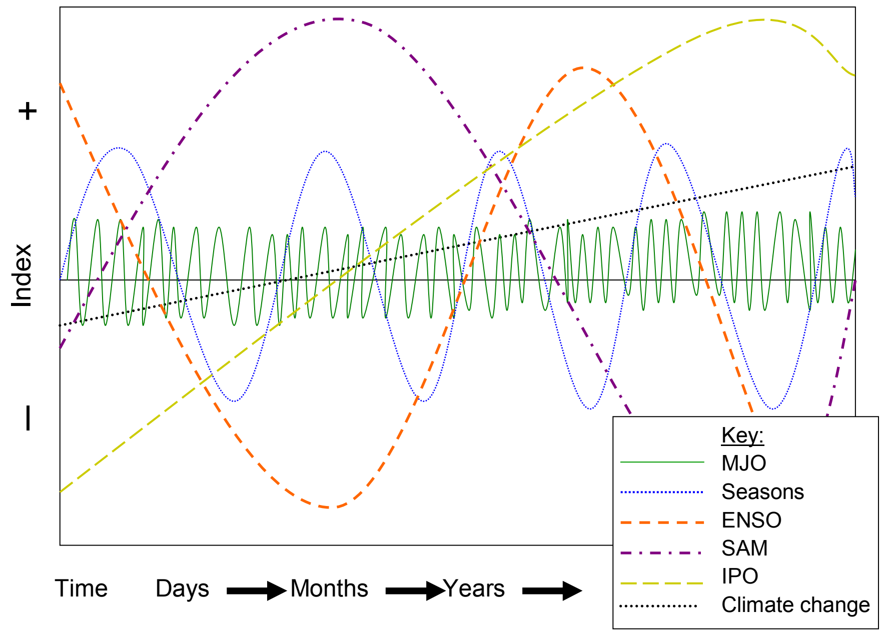


Figure 10.1 Climate mechanisms that affect north-east Queensland. Illustrated in this example, and shown in the key, are climate cycles with the shortest frequency first: the Madden Julian Oscillation (MJO), seasons, Southern Annual Mode (SAM), El Niño Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO). Anthropogenic climate change in this example is shown as a linear increasing trend.

In this study, local climate variables (rainfall, temperature, evaporation, SSTs and freshwater flow), and large-scale climate mechanisms known to influence the region (MJO, ENSO, QBO, LSTR, SAM) were linked to a life cycle model of the species developed on the basis of previous research. This approach increased the likelihood that significant correlations between measures of climate and barramundi catch were due to the impacts from a causal mechanism rather than a spurious result, and reduced the number of variables for analyses.

Short-term climate effects: Princess Charlotte Bay

The first stage of analyses focused on the near-pristine ecosystem of Princess Charlotte Bay in north-east Queensland where the influences from anthropogenic factors such as pollution and habitat degradation were minimal. The years of fisheries catch and effort data as measured by the CFISH program (1989/90 – 2001/02) spanned approximately 80% of the centennial climate variation as measured by rainfall at Musgrave and Laura stations. Analyses of short-term climate variables and catch adjusted for effort (CAE) identified a number of significant correlations two years prior to catch. In each case, significant variables contributed to optimal spawning and/or nursery habitats (high rainfall and flow in the lead up to, and during, the wet season, low evaporation and warm SST), and led to a subsequent increase in catch. In the year of catch there were positive correlations between CAE and both pre-wet and wet season (October – March) freshwater flow and rainfall. This result confirmed earlier observations that increased freshwater flow at this time of year improved connectivity between fresh and estuarine habitats and flushed mature males into the commercial estuarine fishery. Significant correlations between CAE and climate indices (SOI and MJO) were fewer. Pre-wet season SOI (a measure of increased pre-wet season rainfall) was positively and significantly correlated with CAE in the year of catch and the MJO Phase 6 (again a measure of rainfall enhancement for the area) was positively and significantly correlated with CAE the year prior to catch.

Comparative analysis: Fitzroy River area

To determine the validity of transferring the results from Princess Charlotte Bay to other areas, the analyses were repeated for the comparatively degraded Fitzroy River area. In contrast to the results in Princess Charlotte Bay, correlations between climate variables and barramundi CAE were weak, inconsistent and often contrary to the life cycle model. Only pre-wet season (October – December) freshwater flow two years prior to catch was significantly correlated with CAE (positive) and relevant according to the life cycle model. As in Princess Charlotte Bay, flow at this time of year probably breaks the dry season drought, flushes mature males in the estuary for spawning and provides nutrients and inundated wetland habitats. None of the other relevant variables were significantly correlated with CAE. The climatic difference between the regions is minimal and so the result is an indication that anthropogenic modifications to barramundi habitats may have affected the relationship between climate and catch in the area. For this reason, it is recommended that future analyses of the impacts of climate on the fishery be considered to be regionally specific.

Extreme and threshold climate events

Results from the analysis of extreme or threshold climate events on a fishery are also likely to be regionally specific. In Princess Charlotte Bay, pre-wet season (October – December) rainfall, early dry season (April – June) freshwater flow and annual evaporation each had a significant quadratic relationship with barramundi CAE two years later. The peak in CAE occurred in response to 325 mm of rainfall and 250 000 Ml of flow, beyond which catch declined. Above the 325 mm rainfall threshold, a possible decrease in salinity may have resulted in reduced survival of eggs at spawning or an increase in wetland habitat predation due to higher water levels. Flows above 250 000 Ml in the early dry season are likely to have either injured fingerlings as they migrated into rivers, or flushed them into the estuary where, again, they would have been subject to predation.

Annual evaporation also had a non-linear relationship with barramundi CAE in Princess Charlotte Bay. Dramatic declines in catch occurred when annual evaporation exceeded 2 150 mm. A water balance calculation for these years indicated that evaporative demand would have exceeded the average depth of the freshwater wetlands in Princess Charlotte Bay and resulted in a significant decrease in nursery habitat area and young-of-year survival. All three of these thresholds are spatially dependent as they reflect conditions specific to the estuary and wetland habitats of Princess Charlotte Bay. For this reason, they could not be transfered to other areas although the methodology developed to identify them is robust. Spatially independent thresholds such as temperature were not identified in the study for the years of available data. Results from the analyses were combined with those from the analyses of short-term climate effects and included in the life cycle model of the barramundi (Figure 10.2).

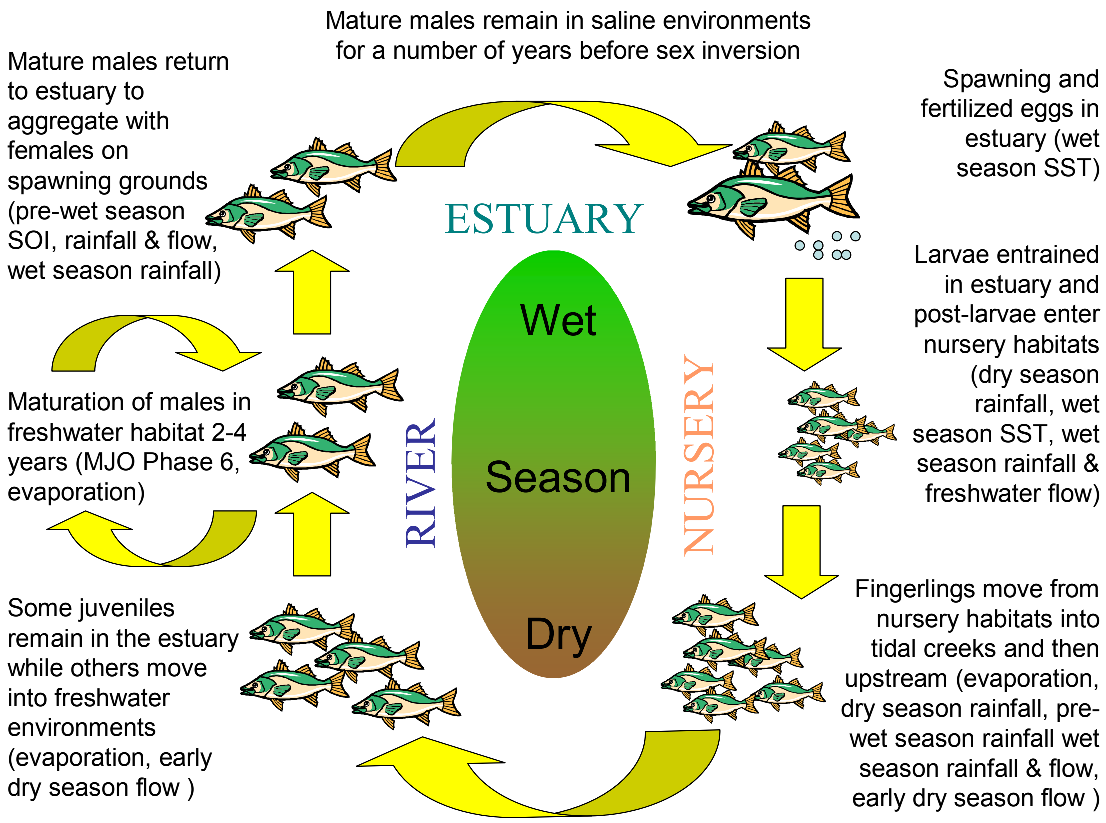


Figure 10.2 Life cycle model of the barramundi showing climate variables identified in the analyses of short-term and threshold climate events as significantly correlated with catch adjusted for effort in the Princess Charlotte Bay area. SOI = Southern Oscillation Index, SST = Sea Surface Temperatures, MJO = Madden Julian Oscillation.

Long term climate effects: North-east Queensland

Once the study had established that short-term climate variability showed a significant correlation with barramundi fishery CAE, indices of long-term, large-scale climate systems known to affect the north-east Queensland region were correlated against long-term Fish Board catch for the whole north-east Queensland region. The long-term analyses identified synchronous long-term variations in catch for many regions along the coast and significant correlations between barramundi catch and indices of the Quasi-biennial Oscillation (QBO – negative) and Latitude of the Sub-tropical Ridge (LSTR – positive) at lags of three to four years and one to four years respectively. A positive QBO is associated with increased tropical cyclone activity in the region and so a negative correlation between the QBO and barramundi CAE indicates that cyclonic events resulted in a reduction in catch – perhaps through the destruction of nursery habitats in the year of, or prior to, spawning or changes to salinity and water depth as identified in the analyses of extreme rainfall events. Positive values of the LSTR are a measure of increased rainfall across the region and so, as in the analyses of short-term climate effects, the positive correlation with CAE indicated that the climate cycle had affected the early life cycle stages of the species perhaps by altering nursery habitats. The results from the long-term analyses also suggest that there is an opportunity to predict north-east Queensland barramundi catch a number of years in advance. In combination with the results from the short-term analyses, a pictorial summary of climate variables affecting the barramundi fishery was developed (Figure 10.3).

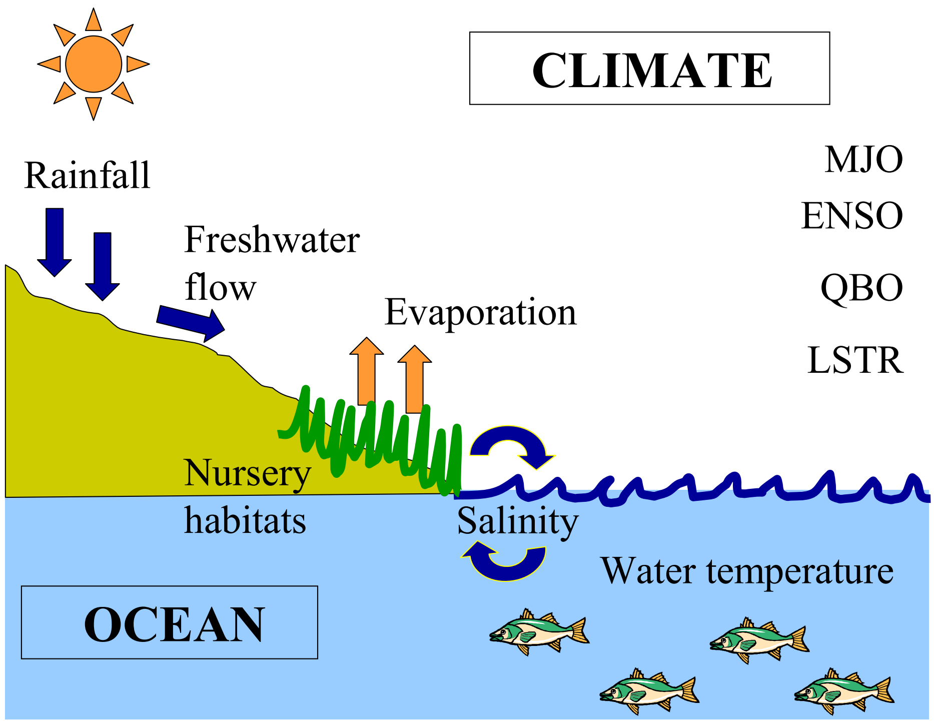


Figure 10.3 Pictorial of each of the climate mechanisms shown from the current research to have a significant effect on commercial barramundi catch in Princess Charlotte Bay. Terrestrial climate measures include rainfall, freshwater flow and evaporation. Atmospheric climate parameters include indices of the Madden Julian Oscillation (MJO), El Niño Southern Oscillation (ENSO), Quasi-biennial Oscillation (QBO) and Latitude of the Sub-tropical Ridge (LSTR). In addition, sea surface temperature was also shown to impact on the fishery.

Predictive model development

A forward stepwise ridge regression model containing only climate variables was built to determine the proportion of the variance in barramundi CAE that could be explained by climate parameters and was used to predict barramundi catch in Princess Charlotte Bay. Up to 62% of the variance in CAE was explained by dry season (July – September) rainfall and annual evaporation both two years prior to catch. A cross validated R^2 of 58% shows that when used in a predictive capacity, the model explained over half the variance in barramundi CAE for the area for the years of data up to two years prior to catch. Due to the limited number of years in the data set, the model was limited to just two steps and so other variables could not be included. However, with longer data sets more of the variance in fishery catch may be explained by including other short-term and/or long-term climate variables. Certainly, the result from this analysis indicates that there is an opportunity to improve the prediction of barramundi catch by including climate parameters into current and future catch models.

Effects of climate change: Princess Charlotte Bay

A suite of synthetic climate change scenarios for the area was run through the barramundi predictive regression model developed for Princess Charlotte Bay to determine the likely change in future catch of the species for the area. Each of the future climate scenarios tested for the years 2030 and 2070 predicted a reduction in barramundi catch due to the projected increase in evaporation for the region and subsequent drying of shallow wetland nursery habitats – despite an increase in rainfall for some scenarios. However, if an availability of suitable habitats is assumed, the future distribution of the species may extend up to 800 km south of the current range (to Newcastle on the east coast and Geraldton in the west) by the year 2070 as SSTs increase. Other changes associated with climate change (such as sea level rise) will alter existing habitats and have currently unknown impacts on the ecological balance of affected areas.

Key findings

In summary, the following key findings address the six objectives of the study and the research questions posed at the end of chapter 2:

1. The life cycle stages of the barramundi most affected by climate are likely to be spawning, young-of-year cohorts and mature males returning to the estuary (catchability);
2. Measures of short-term climate variability (SSTs, rainfall, evaporation and freshwater flow) had a significant correlation with barramundi catch by affecting recruitment (success of spawning and young-of-year survival) two years prior to catch and catchability of mature males in Princess Charlotte Bay;

3. When early life cycle stages of the barramundi are affected by climate (e.g. spawning), there is a lag between the climate event and the impact on catch;
4. Significant relationships between climate and the recruitment or catchability of barramundi in one region do not necessarily apply in other areas due to location specific variations and anthropogenic modifications to habitat;
5. Variation in climate above certain thresholds can result in a non-linear response from the fishery and changes in subsequent catch. Some of these thresholds are spatially specific while others may be transferable;
6. Changes to climate as a result of long-term, large-scale climate systems (the sub-tropical ridge and quasi-biennial oscillation) were significantly correlated with barramundi catch across the north-east Queensland region;
7. Despite limited barramundi catch data (12 years), up to 62% of the variance in barramundi catch in Princess Charlotte Bay was be explained by just two climate variables (annual evaporation and dry season (July – September) rainfall) two years prior to catch;
8. Barramundi catch is likely to be reduced as a result of climate change for those areas where shallow, freshwater nursery habitats are essential for recruitment success – including Princess Charlotte Bay. However, the range of the species may extend south up to 800 km as a result of increasing SST by the year 2070 depending on future emissions of greenhouse gases.

10.3 PAST AND PRESENT MANAGEMENT OF THE BARRAMUNDI FISHERY

Historically, the regulation of the Queensland barramundi fishery focussed on catch levels only. The first Inspectors of Fisheries were appointed to Rockhampton and Gladstone in 1887 under the Fisheries Act to manage the limited trawling for pelagics, seining and gill-netting in estuaries and open beaches, and hand-lining for demersal fish on the inner reefs (Haysom 2001; Quinn and Garrett 1992). Later, commercial-scale fishing was regulated through single desk sales to Fish Board depots opened along the coast in the 1940s (Haysom 2001). However, by the late 1970s, a high number of black-market sales of barramundi (Gray and Spencer 1986), dramatic decreases in catch in some areas, and the limited powers of the Fish Board (Gray and Spencer 1986) fuelled research to determine the sustainability of the fishery. In response to the findings, the Fish Board was disbanded in 1981 and replaced by the East Coast Barramundi Management Plan which limited licences, introduced a closed season from November – January, banned set nets in rivers, extended the breeding ground reserves, introduced a standard minimum mesh size and amateur bag limit, improved enforcement and introduced annual reviews of the fishery (Elmer 1986).

In 1990 the Queensland Fish Management Authority (Q.F.M.A.) undertook a comprehensive review of the East Coast Barramundi Fishery and recommended policies that came into force in July 1992: limited licences (there are currently 596 east coast inshore net licence holders (ABARE 2006)), a closed season from 1 November through 31 January each year to protect pre-spawning mature estuarine fish from being caught, legal size limits to protect both smaller male fish and larger brood stock females (minimum size 580 mm and maximum size 1200 mm), a minimum net size of 115 mm (diagonally stretched length), protected spawning zones that prohibit the use of nets 1000 m either side of a river or creek mouth to prevent inadvertent capture of spawning barramundi during the closed season (Q.F.M.A. 1994). In addition, some rivers were closed to commercial fishermen and allocated exclusively to recreational fishing. These existing polices are currently being reviewed and any changes will be incorporated into the East Coast Inshore Finfish Management Plan due for release late in 2007. A number of dams and rivers in the state are regularly stocked with barramundi fingerlings for recreational fishermen (Pearce 2000; Rutledge 1990) and current recreational regulations include a bag limit, seasonal closure during the wet season and upper and lower size limits. Limitations to fishing have also been introduced through the formation of national parks, marine parks, marine estuarine parks, fisheries nursery habitats and habitat reserves. Various exclusions are associated with each area. However, variability in the climate is not considered in the management of the barramundi fishery. The following section draws together the conclusions of this study to outline some management recommendations for the east coast barramundi fishery.

10.4 IMPLICATIONS OF THIS RESEARCH FOR FUTURE MANAGEMENT OF THE BARRAMUNDI FISHERY

Preservation of wetlands

This study has confirmed how important conditions in the nursery habitat are for subsequent barramundi catch. An estimated 50% of estuaries in Australia are now classified as degraded as a result of human pressures (DEH 2001). In some habitats there has been a reduction of up to 70% of wetland area when compared to pre-European times (DEH 2001). To preserve the quality and availability of wetland habitats the drainage of wetlands for agricultural and other development (particularly between Townsville and Cairns (Russell, Hales *et al.* 1996) and other discrete areas such as the Fitzroy River estuary), construction of impediments to the flow of water including dams and barrages and the creation of ponded pastures that preclude fish from entering the habitat need to cease. A significant reduction in the catch of barramundi and other species has also occurred in response to less obvious impacts that also need to be managed such as pollution, turbidity from erosion, clearing of riparian zones, nitrification of the water, algal blooms, and the incursion of vegetative pest species such as water hyacinth, salvinia (Hogan and Graham 1994) and pond apple (Russell, Hales *et al.* 1996). Numerous other studies (e.g. Garrett 1991; Quinn and Garrett 1992; Russell and Garrett 1988) have also identified the preservation of wetlands as a priority to ensure the protection of fisheries nursery habitats, and the findings from this study reinforce these recommendations.

Preservation of environmental flows

Freshwater flow has been shown in this study to be significantly and positively correlated with barramundi catch. The preservation of environmental flows is therefore seen as an important aspect of maintaining healthy barramundi populations. This conclusion was also reported by researchers in the Fitzroy River area who studied the role of freshwater flows and estuary ecosystem health on barramundi catch (Robins, Halliday *et al.* 2005; Staunton-Smith, Robins *et al.* 2004). It is worth noting that *when* freshwater flows occur, as well as the *amount* of water, has a significant impact on the species.

Regulation of fishing pressure

Results from the forward stepwise ridge regression modelling indicate that over half of the variance in barramundi catch in Princess Charlotte Bay can be explained by climate variables two years prior to harvest. Currently, however, climate variability is not included in the management of the fishery. With the understanding that climate is driving a large proportion of the variability seen in barramundi catch (and possibly the catch of other species), fisheries managers have the opportunity to improve the sustainable harvest of fish in response to climatic conditions. Terrestrial farming systems have been managed in response to forecasts of rainfall variability for over ten years and results have been both reductions in financial risk and improved sustainability (Meinke and Hochman 2000). To include climate variability into the management of a fishery would require a number of things. First, an accurate measure of the climate in the region and an understanding of which climate variables affect the fishery. Secondly, a measure of fish population in response to the climate (a catch model that includes relevant climate drivers), and finally, an adaptive management system that allowed for changes in fishing pressure from one year to the next.

Consideration of climate change

Impacts on the fishery as a result of anthropogenic climate change will quite likely alter the relationships between climate parameters and barramundi catch identified in both this and other studies. As ecosystems are altered, extreme events become more common and the mean state of various climate parameters change projections for future catch will need to be adjsuted. An increase in flood frequency and corresponding sediment loads may have a significant impact on barramundi productivity via ecosystem health (Phillip Ford, Senior Marine Researcher, CSIRO, pers. comm. July 2005). However, barramundi populations are also likely to adapt to some degree to the expected changes. Some populations are believed to live entirely in a marine salt marsh habitat (Neil Gribble, Senior Fisheries Research Officer, Department of Primary Industries and Fisheries, pers. comm. December 2006) and so reductions in current freshwater habitat as a result of sea level rise, increased evaporation and diminished freshwater flows may be overcome in some areas. However, to know if this is the case or not, areas at high risk from climate change impacts need to be identified and a monitoring program put in place. In addition, current seasonal closures and protected fish habitats will need to be reviewed regularly to ensure fish are not spawning earlier or later, or migrating to new areas as a result of changes in the climate.

10.5 RECOMMENDATIONS FOR FUTURE RESEARCH

Already, the Gulf of Carpentaria commercial barramundi organisation (GulfMac) has requested that the work undertaken in this study be replicated for the Gulf of Carpentaria barramundi fishery. In addition, there are a number of research gaps that have been identified during the course of this research that will require attention to ensure the future sustainability of the barramundi and other north-eastern fin-fisheries:

- Future barramundi catch can be used to validate the results found in this and other studies;
- Climate change will probably affect the relationships between climate variables and barramundi catch and hence models developed on the basis of climate will need to be reviewed regularly for reliability;
- Targeted studies of the impacts of climate on other inshore fin-fisheries species will be required as there is currently limited knowledge of the effects and hence a limited understanding of the likely impacts of climate change on these species;
- The effects of extreme or threshold climate events for the barramundi in other areas of Australia, and for other species, have not been quantified and so are unknown at this stage;
- The influence from long-term, large-scale climate systems has not been considered for other inshore fin-fisheries in Australia and may provide the opportunity to develop long-term predictive models for catch.
- The impact of altering freshwater flows and/or wetland habitats should be quantified carefully prior to approving changes, to ensure impacts to inshore fisheries is minimal;
- There is the opportunity to include measures of climate into fisheries models where they have been shown to influence the fishery;
- The spatial analysis of wetlands using MODIS or similar remote sensing technology might be used for regular updates on the state of these habitats as a means of monitoring likely changes to fish populations;

- Options for extending the times series of fin-fish data for the Australian region should be pursued including the possibility of using coral or sediment cores as has been done overseas, or by analysing aboriginal middens as a source of historical catch.

In concluding, the results from this research have shown for the first time that climate variability at both short and long time scales can have a significant and at times non-linear impact on the catch of barramundi in north-east Queensland. There is the opportunity to improve the sustainable management of the fishery by incorporating measures of climate into both catch models and adaptive management strategies. A number of papers will be written and submitted for publication on the basis of this work and this thesis and recommendations for management will be presented for consideration to reviewers of the East Coast Inshore Finfish Management Plan.

REFERENCES

ABARE (2006) 'Australian Fisheries Statistics 2005.' Australian Bureau of Agricultural and Resource Economics, Canberra.

Abbs DJ (2004) The effect of climate change on the intensity of extreme rainfall events. In 'Climate and water: 16th Australian New Zealand Climate Forum'. Lorne, Victoria. (ANZCF 2004 Conference Committee)

ACG (2005) 'Climate Change Risk and Vulnerability.' Allen Consulting Group, Canberra.

Agcopra C, Balston JM, Bowater R, Rodgers LJ, Williams AAJ (2005) Predictive system for aquaculture ponds. In 'Queensland Aquaculture News'. pp. 3.

Aita MN, Yamanakaa Y, Kishia MJ (2005) Interdecadal variation of the lower trophic ecosystem in the northern Pacific between 1948 and 2002, in a 3-D implementation of the NEMURO model. *Geophysical Research Abstracts* **7**.

Allan RJ (1988) El Niño Southern Oscillation influences in the Australasian region. *Progress in Physical Geography* **12**, 313-349.

Allan RJ (1991) Australasia. In 'Teleconnections linking worldwide climate anomalies: scientific basis and societal impact'. (Eds MH Glantz, RW Katz and N Nicholls) pp. 73-120. (Cambridge University Press: Cambridge)

Allan RJ (2000) ENSO and climatic variability in the last 150 years. In 'El Niño and the Southern Oscillation: Multiscale Variability, Global and Regional Impacts'. (Eds HF Diaz and V Markgraf) pp. 3-55. (Cambridge University Press: Cambridge)

ANCA (1996) 'A directory of important wetlands in Australia.' (Australian Nature Conservation Agency: Canberra)

Anyamba EK, Weare BC (1995) Temporal variability of the 40-50 Day Oscillation in tropical convection. *International Journal of Climatology* **15**, 379-402.

Baldwin MP, Gray LJ*, et al.* (2001) The Quasi-biennial oscillation. *Review of Geophysics* **39**, 179-229.

Balston JM, Williams AAJ (2005) Modelling impacts of climate variability on the commercial barramundi (*Lates calcarifer*) fishery of north-eastern Queensland. In 'International congress on modelling and simulation (MODSIM): Advances and Applications for Management and Decision Making.' Melbourne, Australia. (Eds A Zerger and RM Argent) p. 456. (Modelling and Simulation Society of Australia and New Zealand Inc.)

Barber RT, Chavez FP (1983) Biological consequences of El Niño. *Science* **222**, 1203-1210.

Bardach JE, Santerre RM (1981) Climate and the fish in the sea. *BioScience* **31**, 206-215.

Barlow CG, Lisle A (1987) Biology of the Nile Perch *Lates niloticus* (Pisces: Centropomidae) with reference to its proposed roles as a sport fish in Australia. *Biological Conservation* **39**, 269-289.

Barlow CG, Rimmer MA (1989) 'Larval and juvenile culture of barramundi *Lates calcarifer* (Bloch).' Fishing Industry Research and Development Council, 89/67.

Beamish RJ, Bouillon DR (1993) Pacific salmon production trends in relation to climate. *Canadian Journal of Fisheries and Aquatic Sciences* **50**, 1002-1016.

Beamish RJ, McFarlane GA, Thompson RE (1999) Recent declines in the recreational catch of coho salmon (*Oncorhynchus kisutch*) in the Strait of Georgia are related to climate. *Canadian Journal of Fisheries and Aquatic Sciences* **56**, 506-515.

Beamish RJ, Noakes DJ, McFarlane GA, Klyashtorin L, Ivanov VV, Kurashov V (1999) The regime concept and natural trends in the production of Pacific salmon. *Canadian Journal of Fisheries and Aquatic Sciences* **56**, 516-526.

Bell FH, Pruter AT (1958) Climatic temperature changes and commercial yields of some marine fisheries. *Journal of Fisheries Research Board Canada* **15**, 625-683.

BOM (1988) 'Climatic atlas of Australia.' (Bureau of Meteorology, Department of Administrative Services: Canberra)

BOM (2005) Bureau of Meteorology Website viewed 2005. http://www.bom.gov.au/silo/products/cli_chg/

Bucher D, Saenger P (1991) An inventory of Australian estuaries and enclosed marine waters: an overview of results. *Australian Geographical Studies* **29**, 370-381.

Bucher D, Saenger P (1994) A classification of tropical and subtropical Australian estuaries. *Aquatic Conservation: Marine and Freshwater Ecosystems* **4**, 1-19.

Cabrala HN, Vasconcelosa R*, et al.* (2007) Rising water temperatures have dramatically changed the species of fish in Portugal's Tejo River estuary, the biggest in Western Europe, a researcher said yesterday. *Journal of Sea Research* **57**, 209-217.

Cai W (2003) Australian droughts, climate variability and climate change: insights from CSIRO's climate models. In 'Science for Drought'. Brisbane. (Eds R Stone and IJ Partridge) p. 173. (Queensland Department of Primary Industries)

Cai W, Crimp S*, et al.* (2003) 'Climate change in Queensland under enhanced greenhouse conditions. Final Report 2002-2003.' CSIRO, C/0708, Aspendale.

Cappo M, Alongi DM, McWilliams D, Duke N (1998) 'A review and synthesis of Australian fisheries habitat research.' Australian Instituite of Marine Science, FRDC 95/005, Townsville.

Caputi N, Brown RS (1993) The effect of environment on puerulus settlement of the western rock lobster (*Panulirus cygnus*) in Western Australia. *Fisheries Oceanography* **2**, 1-10.

Caputi N, Chubb CF, Brown RS (1993) Relationships between spawning stock, envirnonment, recruitment and fishing effort for the western rock lobster, *Panulirus cygnus*, fishery in Western Australia. In 'Fourth International Workshop on Lobster Biology and Management' pp. 213-226

Caputi N, Chubb CF, Pearce A (2001) Environmental effects on recruitment of the western rock lobster, *Panulirus cygnus*. *Marine and Freshwater Research* **52**, 1167-1174.

Caputi N, Fletcher WJ, Pearce A, Chubb CF (1996) Effect of the Leeuwin Current on the recruitment of fish and invertebrates along the Western Australian coast. *Marine Freshwater Research* **47**, 147-155.

Caputi N, Penn JW, Joll LM, Chubb CF (1998) Stock-recruitment-environment relationships for invertebrate species of Western Australia. In 'North Pacific Symposium on Invertebrate Stock Assessment and Management'. (Eds GS Jamieson and A Campbell) pp. 247-255. (Canadian Special Publication of Fisheries Aquatic Science)

Castro LR, Hernandez EH (2000) Early life survival of the anchoveta *Engraulis ringens* off central Chile during the 1995 and 1996 winter spawning season. *Transactions of the American Fisheries Society* **129**, 1107-1117.

Castro LR, Salinas GR, Hernandez EH (2000) Environmental influences on winter spawning of the anchoveta *Engraulis ringens* off central Chile. *Marine Ecology Progess Series* **197**, 247-258.

Chandler RE, Wheater HS (2002) Analysis of rainfall variability using generalised linear models: A case study from the west of Ireland. *Water Resources Research* **38**, 1-11.

Chase TN, Knaff JA, Pielke RA, Kalnay E (2003) Changes in global monsoon circulations since 1950. *Natural Hazards* **29**, 229-254.

Chavez FP, Ryan J, Lluch-Cota SE, Niquen MC (2003) From anchovies to sardines and back: Multidecadal change in the Pacific Ocean. *Science* **299**, 217-221.

Chenoweth SF, Hughes JM, Keenan CP, Lavery S (1998) Concordance between dispersal and mitochondrial gene flow: Isolation by distance in a tropical teleost, *Lates calcarifer* (Australian barramundi). *Heredity* **80**, 187-197.

Chiew FHS, Harrold TI, Siriwardena L, Jones RN, Srikanthan R (2003) Simulation of climate change impact on runoff using rainfall scenarios that consider daily patterns of change from GCMs. In 'International Congress on Modelling and Simulation (MODSIM)'. Townsville, Queensland pp. 154-159. (Modelling and Simulation Society of Australia and New Zealand)

CHRIS (2002) The Coastal Habitat Resources Information System viewed 2004. http://chrisweb.dpi.qld.gov.au/chris/

Church JA, Hunter J, Mc Innes K, White NJ (2004) Sea-level rise and the frequency of extreme events around the Australian coastline. In 'National Coastal Conference - Coast to Coast,'. Hobart, Australia

Clark ME, Rose KA, Levine DA, Hargrove WW (2000) Predicting climate change effects on Appalachian trout: combining GIS and individual-based modeling. *Ecological Applications* **11**, 161-178.

Clewett JF, Clarkson NN, George DA, Ooi SH, Owens DT, Partridge IJ, Simpson GB (2003) 'Rainman StreamFlow version 4.3: a comprehensive climate and streamflow analysis package on CD to assess seasonal forecasts and manage climate risk.' Queensland Department of Primary Industries, Brisbane, Australia.

Clewett JF, Clarkson NN, Owens DT, Abrecht DG (1994) 'Australian Rainman: Rainfall information for better management.' Queensland Department of Primary Industries, Brisbane, Australia.

Coates M, Unwin L (1991) Ponded pastures and the habitat requirements of barramundi, *(Lates calcarifer*). In 'Probing Ponded Pastures Workshop'. University of Central Queensland pp. 82-88

Cordery I (1998) Forecasting precipitation from atmospheric circulation and SOI. In 'Hydrology in a changing environment'. Exeter, United Kingdom. (Eds H Wheater and C Kirby) pp. 63-69. (British Hydrological Society)

Crimp S, Balston JM, Ash A (2003) 'A study to determine the scope and focus of an integrated assessment of climate change impacts and options for adaptation in the Cairns and Great Barrier Reef region.' Australian Greenhouse Office, Canberra.

CSIRO (2006a) REEFCLIM. In. (Aspendale)

CSIRO (2006b) Standard Fish Names in Australia (commercial species) viewed 2006. http://www.marine.csiro.au/caabsearch/caab_search.fish_names_list

Das SC (1956) Statistical analysis of Australian pressure data. *Australian Journal of Physics* **9**, 394-399.

Davis S (1981) 'The habitats of barramundi in the Crocodile Islands area.' Milingimbi.

Davis TLO (1982) Maturity and sexuality in barramundi, *Lates calcarifer* (Bloch), in the Northern Territory and South-eastern Gulf of Carpentaria. *Australian Journal of Marine and Freshwater Research* **33**, 529-545.

Davis TLO (1984) Estimation of fecundity in barramundi *Lates calcarifer* (Bloch), using an automatic particle counter. *Australian Journal of Marine and Freshwater Research* **35**, 111-118.

Davis TLO (1985) Seasonal changes in gonad maturity, and abundance of larval and early juveniles of barramundi, *Lates calcarifer* (Bloch), in Van Diemen Gulf and the Gulf of Carpentaria. *Australian Journal of Marine and Freshwater Research* **36**, 177-190.

Davis TLO (1986) Migration patterns in barramundi, *Lates calcarifer* (Bloch), in Van Diemen Gulf, Australia, with estimates of fishing mortality in specific areas. *Fisheries Research* **4**, 243-258.

Davis TLO (1988) Temporal changes in the fish fauna entering a tidal swamp system in tropical Australia. *Environmental Biology of Fishes* **21**, 161-172.

Davis TLO, Kirkwood GP (1984) Age and growth studies on barramundi, *Lates calcarifer* (Bloch), in Northern Australia. *Australian Journal of Marine and Freshwater Research* **35**, 673-689.

De GK (1971) On the biology of post-larval and juvenile stages of *Lates Calcarifer* (Bloch). *Journal of the Indian Fisheries Association* **1**, 54-64.

DEH (2001) 'Coasts and Oceans, Australia State of the Environment Report 2001.' Australian State of the Environment Committee, Department of the Environment and Heritage, Canberra.

Donald A, Meinke H, Power B, de Maia A, Wheeler MC, White N, Stone R, Ribbe J (2006) Near global impact of the Madden-Julian oscillation on rainfall. *Geophysical Research Letters* **33**, L09704, doi:10.1029/2005GL025155.

Done T, Whetton P, Jones R, Berkelmans R, Lough J, Skirving W, Wooldridge S (2003) 'Global Climate Change and Coral Bleaching on the Great Barrier Reef.' Queensland Government Department of Natural Resources and Mines, Brisbane.

Downey WK (1983) Meteorology of the Great Barrier Reef and Western Coral Sea. In 'Inaugural Great Barrier Reef Conference'. Townsville. (Eds JT Baker, RM Carter, PW Sammarco and KP Stark) pp. 421-433. (James Cook University Press)

DPI (1993) 'The Condition of River Catchments in Queensland.' Department of Primary Industries, Brisbane.

DPI (1995a) 'Overview of water resources and related issues : The Southern Wet Tropics region.' (Department of Primary Industries Water Resources: Brisbane)

DPI (1995b) 'Overview of water resources and related issues: The Northern Wet Tropics region.' (Department of Primary Industries Water Resources: Brisbane)

Drinkwater KF, Frank KT (1994) Effects of river regulation and diversion on marine fish and invertebrates. *Aquatic Conservation: Marine and Freshwater Ecosystems* **4**, 135-151.

Drinkwater KF, Myers RA (1987) Testing predictions of marine fish and shellfish landings from environmental variables. *Canadian Journal of Fisheries and Aquatic Sciences* **44**, 1568-1573.

Drosdowsky W (2005) The latitude of the sub-tropical ridge over eastern Australia: The L index revisited. *International Journal of Climatology* **25**, 1291-1299.

Dunstan DJ (1959) 'The barramundi *Lates calcarifer* (Bloch) in Queensland waters.' CSIRO, Melbourne.

Elmer M (1986) Barramundi (*Lates calcarifer)* fisheries management in Queensland, Australia. In 'Management of wild and cultured Sea Bass/Barramundi *(Lates calcarifer)*'. Darwin, Australia. (Eds JW Copland and DL Grey) pp. 96-98. (Australian Centre for International Agricultural Research)

Enfield DB, Cid-Serrano L (2006) Projecting the risk of future climate shifts. *International Journal of Climatology* **26**, 885-895.

Evans JC, Allan RJ (1992) El Niño/Southern Oscillation modification to the structure of the monsoon and tropical cyclone activity in the Australasian region. *International Journal of Climatology* **12**, 611-623.

Feenstra JF, Burton I, Smith JB, Tol RSJ (Eds) (1998) 'Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies (2 edn).' (United Nations Environment Program)

Finlayson M (2003) Climate impacts on Australia's tropical wetlands. In 'Climate Impacts on Australia's Natural Resources: Current and Future Challenges'. Gold Coast pp. 49-50. (The Standing Committee on Natural Resources Management)

Finney BP, Gregory-Eaves I, Douglas MSV, Smiol JP (2002) Fisheries productivity in the north-eastern Pacific Ocean over the past 2,200 years. *Nature* **416**, 729-733.

Fishbase (2005) Fishbase viewed 2005. http://www.fishbase.org/search.php

Fisher JP, Pearcy WG (1988) Growth of juvenile Coho Salmon *(Oncorhynchus kisutch)* off Oregon and Washington, USA, in years of differing coastal upwelling. *Canadian Journal of Fisheries and Aquatic Sciences* **45**, 1036-1044.

Fletcher WJ, Tregonning RJ, Sant GJ (1994) Interseasonal variation in the transport of pilchard eggs and larvae off southern Western Australia. *Marine Ecology Progress Series* **111**, 209-224.

Folland C, Parker DE, Colman AW, Washington R (1998) 'Large scale modes of ocean surface temperature since the late nineteenth century.' Hadley Centre, London, United Kingdom.

Ford A (1999) 'Modelling the Environment: An Introduction to System Dynamics Modelling of Environmental Systems.' (Island Press: Washington D.C.)

Fournier DA, Archibald C (1982) A general theory for analyzing catch at age data. *Canadian Journal of Fish Aquatic Science* **39**, 1195-1207.

Fox WW (1970) An exponential surplus-yield model for optimizing exploited fish populations. *Transactions of the American Fisheries Society* **1**, 80-88.

Fox WW (1975) Fitting the generalised stock production model by least-squares and equilibrium approximation. *Fishery Bulletin* **73**, 23-36.

Frye R (1983) Climatic change and fisheries management. *Natural Resources Journal* **23**, 77-96.

Garrett R (1991) Utilization of wetland habitats by coastal fishes in northern Australia. In 'Proceedings of the Probing Ponded Pastures Workshop'. Rockhampton pp. 94-114. (University of Central Queensland.)

Garrett RN (1986) Reproduction of Queensland barramundi (*Lates calcarifer)*. In 'Management of wild and cultured Sea Bass/Barramundi *(Lates calcarifer)*'. Darwin, Australia. (Eds JW Copland and DL Grey) pp. 38-43. (Australian Centre for International Agricultural Research)

Garrett RN (1992) 'Biological investigations of the barramundi *Lates calcarifer* in the Gulf of Carpentaria: A summary report.' Queensland Fish Management Authority, Cairns, Australia.

Garrett RN, Mackinnon MR, Russell DJ (1987) Wild barramundi breeding and its implications for culture. In 'Australian Fisheries'. pp. 4-6.

Garrett RN, Russell DJ (1982) 'Premanagement investigations into the barramundi *Lates calcarifer* (Bloch) in northeast Queensland waters: a report to the Fishing Industry Research Committee.' Queensland Department of Primary Industries, Brisbane.

Gifford R, Farquhar GD, Nicholls N, Roderick ML (2004) Workshop summary on pan evaporation: An example of the detection and attribution of climate change variables. In 'Pan Evaporation: An example of the detection and attribution of trends in climate variables'. Canberra. (Ed. R Gifford) p. 81pp. (Australian Academy of Science and the Australian Greenhouse Office)

Glantz MH, Feingold LE (1990) 'Climate variability, climate change and fisheries.' (Environmental and Societal Impacts Group, NCAR: Boulder, Colorado)

Gong D, Wang S (1998) Antarctic oscillation: concept and applications. *Chinese Science Bulletin* **43**, 734-738.

Gong D, Wang S (1999) Definition of Antarctic Oscillation Index. *Geophysical Research Letters* **26**, 459-462.

Graham NE, White WB (1988) The El Niño cycle: A natural oscillator of the Pacific Ocean-atmosphere system. *Science* **240**, 1293-1302.

Grant AP, Walsh KJE (2001) Interdecadal variability in north-east Australian tropical cyclone formation. *Atmospheric Science Letters* **2**, 9-17.

Gray M, Spencer S (1986) The structure and economics of fish and seafood marketing in Queensland. In 'Fisheries Management: Theory and Practice in Queensland'. (Ed. TJA Hundloe). (Griffith University Press: Brisbane)

Gray WM (1988) Seasonal frequency variations in the 40-50 Day Oscillation. *Journal of Climatology* **8**, 511-519.

Gray WM, Scheaffer JD (1991) El Niño and QBO influences on tropical cyclone activity. In 'Teleconnections linking worldwide climate anomalies: scientific basis and societal impact'. (Eds MH Glantz, RW Katz and N Nicholls) pp. 257-284. (Cambridge University Press: Cambridge)

Greenwood PH (1976) A review of the family Centropomidae (Pices, Perciformes). *Bulletin of The British Museum (Natural History), Zoology* **29**, 81.

Grey DL (1986) An overview of *Lates calcarifer* in Australia and Asia. In 'Management of wild and cultured Sea Bass/Barramundi *(Lates calcarifer)*'. Darwin, Australia. (Eds JW Copland and DL Grey) pp. 15-21. (Australian Centre for International Agricultural Research)

Grey DL, Griffin RK (1979) 'A review of the Northern Territory barramundi fishery.' Department of Industrial Development, Fishery Report No.1, Darwin.

Gribble NA, Rasheed M, Balston JM (2005) Drought impacts on Marine Ecosystems of the southern Gulf of Carpentaria. In 'Australian Society of Fish Biology'. Darwin

Griffin RK (1982) 'A survey of amateur angling for Barramundi (*Lates calcarifer*) in the Northern Territory.' Northern Territory Department of Primary Production, Technical Report No. 2, Darwin.

Griffin RK (1985) The importance of mangrove / coastal wetland to three commercial fisheries in the Northern Territory particularly for barramundi (*Lates calcarifer*). In 'Coasts and tidal wetlands of the Australian monsoon region'. (Eds KN Bardsley, JDS Davie and CD Woodroffe). (Australian National University: Darwin)

Griffin RK (1986) Barramundi (*Lates calcarifer)* research in Northern Territory, Australia. In 'Management of wild and cultured Sea Bass/Barramundi *(Lates calcarifer)*'. Darwin, Australia. (Eds JW Copland and DL Grey) pp. 87-91. (Australian Centre for International Agricultural Research)

Griffin RK (1987) Life history, distribution, and seasonal migration of barramundi in the Daly River, Northern Territory, Australia. In 'American Fisheries Society Symposium'. (Ed. MJ Dadswell) pp. 358-363

Griffin RK (1993) Modelling the Northern Territory barramundi fishery: 1978-1992. In 'Population dynamics for fisheries management. Australian Society for Fish Biology'. North Beach, Perth, Western Australia. (Ed. DA Hancock) pp. 188-194. (Australian Society for Fish Biology)

Griffin RK (1995) Wetland habitats and barramundi. In 'Wetland Research in the Wet-dry Tropics of Australia Workshop 22-24 March 1995'. Jabiru, Northern Territory, Australia pp. 64-68. (Environmental Research Institute of the Supervising Scientist)

Griffin RK, Kelly M (2001) 'Fishery Assessment Report Northern Territory Barramundi Fishery - 1999.' Northern Territory Department of Primary Industries and Fisheries, 56, Darwin.

Gunter G, Hilderbrand HH (1954) The relation of total rainfall of the state and catch of the marine shrimp (*Penaeus setiferus*) in Texas waters. *Bulletin of the Marine Science of the Gulf and Caribbean* **4**, 95-103.

Hall V, Gribble NA, Peverell S (1998) 'Tropical Resource Assessment Program - Annual Report 1998.' Department of Primary Industries, FRDC Project 95/049, Brisbane.

Hare SR, Mantua NJ (2000) Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress In Oceanography* **47**, 103-145.

Harris GP, Davies P, Nunuz M, Meyers G (1988) Interannual variability in climate and fisheries in Tasmania. *Nature* **333**, 754-757.

Harris GP, Griffiths FB, Clementson LA (1992) Climate and the fisheries off Tasmania - Interactions of physics, food chains and fish. *South African Journal of Marine Science* **12**, 585-597.

Haysom N (2001) 'Trawlers, Trollers and Trepangers. The story of the Queensland commercial fishing industry pre-1988.' (Department of Primary Industries: Brisbane)

Heap A, Bryce S, Ryan D, Radke L, Smith C, Smith R, Harris P, Heggie D (2001) 'Australian Estuaries and Coastal Waterways: A Geoscience Perspective for Improved and Integrated Resource Management.' Australian Geological Survey Organisation, 2001/7, Canberra, Australia.

Henderson-Sellers A, McGuffie K (2004) Changes in clouds. In 'Pan Evaporation: An example of the detection and attribution of trends in climate variables'. Canberra. (Ed. R Gifford) pp. 54-62. (Australian Academy of Science and the Australian Greenhouse Office)

Hendon H, Liebmann B (1990) The Intraseasonal (30-50 day) Oscillation of the Australian summer monsoon. *Journal of the Atmospheric Sciences* **47**, 2909-2923.

Herbert JM, Dixon RW (2003) Is the ENSO phenomenon changing as a result of global warming? *Physical Geography* **23**, 196-211.

Higgs J (2001) 'Recreational Catch estimates for QLD residents.' Queensland Department of Primary Industries and Fisheries, Brisbane.

Hilbert DW (2002) Non-linear systems. In 'Encyclopaedia of Global Environmental change. The Earth system: biological and ecological dimensions of global environmental change'. (Eds HA Mooney and JG Canadell) pp. 450-455. (John Wiley & Sons, Ltd.: Chichester)

Hjort J (1926) Fluctuations in the year classes of important food fishes. *Journal du Conseil International pour L'Exploration de la Mer* **1**, 3-38.

Hobday A, Matear R (2006) 'Review of Climate Impacts on Australian Fisheries and Aquaculture: implications for the effects of Climate Change.' Australian Greenhouse Office, Canberra.

Hogan A, Graham P (1994) 'Herbert river floodplain fish distributions and fish habitat.' Queensland Department of Primary Industries, Walkamin.

Holland GJ (1986) Interannual variability of the Australian summer monsoon at Darwin: 1952-82. *Monthly Weather Review* **114**, 594-604.

Holling CS (1973) Resilience and stability of ecological systems. *Annual review of ecology and systematics* **4**, 1-23.

Hsieh C, Glaser SM, Lucas AJ, Sugihara G (2005) Distinguishing random environmental fluctuations from ecological catastrophes for the North Pacific Ocean. *Nature* **435**, 336-340.

Huber M, Caballero R (2003) Eocene El Niño: Evidence for robust tropical dynamics in the "Hothouse". *Science* **299**, 877-881.

Hughes L (2003) Climate change and Australia: Trends, projections and impacts. *Austral Ecology* **28**, 423-443.

Humphries P, Lake S, Growns S (2001) 'Effect of flow manipulation on the biota of a lowland river.' Land and Water Resources Research and Development Corporation.

Hundloe TJA (1985) 'Fisheries of the Great Barrier Reef.' (Great Barrier Reef Marine Park Authority: Brisbane)

IPCC (2001a) 'Climate change: Impacts, Adaptation and Vulnerability.' Intergovernmental Panel on Climate Change, Geneva, Switzerland.

IPCC (2001b) 'Climate change: The scientific basis.' Intergovernmental Panel on Climate Change, Geneva, Switzerland.

IPCC (2003) 'IPCC workshop on changes in extreme weather and climate events.' Beijing, China.

IPCC (2007) 'Climate change 2007: The physical science basis.' Intergovernmental Panel on Climate Change, Geneva, Switzerland.

IRI (2001) Climate and Fisheries: Interacting paradigms, scales and policy approaches. In 'The IRI-IPRC Pacific Climate-Fisheries Workshop'. Honolulu. (Eds A Bakun and K Broad) p. 66. (International Research Institute for Climate Prediction)

Jenkins GP (2005) Influence of climate on the fishery recruitment of a temperate, seagrass-associated fish, the King George whiting *Sillaginodes punctata*. *Marine Ecology Progress Series* **288**, 263-271.

Johnston R (2004) Distribution and tidal migration of fishes across intertidal zones. In 'Annual Coastal CRC Workshop 13-16 September, 2004'. Nerang, Queensland. (CRC for Coastal zone estuary and waterways management)

Johnston R (2005) Discrete depth distributions of aquatic fauna within isolated pools. In 'Research for Coastal Management - Coastal CRC conference'. Coolangatta, Queensland p. 60. (CRC for Coastal Zone Estuary and Waterway Management)

Joll LM, Caputi N (1995) Environmental influences on recruitment in the saucer scallop (*Amusium balloti*) fishery of Shark Bay, Western Australia. In 'Shellfish life histories and shellfishery models'. Moncton, New Brunswick, Denmark. (Eds DE Aiken, SL Waddy and GY Conan) pp. 47-53. (ICES Copenhagen (Denmark))

Jones C, Waliser DE, Lau KM, Stern W (2004) Global occurrences of extreme precipitation and the Madden-Julian Oscillation: Observations and Predictability. *Journal of Climate* **17**, 4575-4589.

Jones K, Everingham Y (2005) Can ENSO combined with Low-Frequency SST signals enhance or suppress rainfall in Australian sugar growing areas? In 'International congress on modelling and simulation (MODSIM): Advances and Applications for Management and Decision Making.' Melbourne, Australia. (Eds A Zerger and RM Argent) pp. 1660-1666. (Modelling and Simulation Society of Australia and New Zealand Inc.)

Jorge da Silva A (1986) 'River runoff and shrimp abundance in a tropical coastal ecosystem - the example of the Sofala Bank (Central Mozambique).' (Springer-Verlag: Heidelberg)

Kapetsky JM (2000) Present applications and future needs of meteorological and climatological data in inland fisheries and aquaculture. *Agricultural and Forest Meteorology* **103**, 109-117.

Keenan CP (1992) Reassessment of population structure in Australian barramundi, *Lates calcarifer* (Bloch). In '19th Annual conference and workshop for the Australian Society for Fish Biology'. Victor Harbour, South Australia pp. 33-37. (Australian Society for Fish Biology)

Keenan CP (1994) Recent evolution of population structure in Australian barramundi, *Lates calcarifer* (Bloch): an example of isolation by distance in one dimension. *Australian Journal of Marine and Freshwater Research* **45**, 1123-1148.

Keenan TD, Brody LR (1988) Synoptic-scale modulation of convection during the Australian summer monsoon. *Monthly Weather Review*, 71-85.

Kershaw AP (1985) An extended late Quaternary vegetation record from north-eastern Queensland and its implications for the seasonal tropics of Australia. *Proceedings of the Ecological Society of Australia* **13**, 179-189.

Kim J-Y, Kang Y-S, Oh H-j, Suh Y-S, Hwang J-D (2005) Spatial distribution of early life stages of anchovy (*Engraulis japonicus*) and hairtail (*Trichiurus lepturus*) and their relationship with oceanographic features of the East China Sea during the 1997 –1998 El Niño Event. *Estuarine, Coastal and Shelf Science* **63**, 13-21.

Kingsford MJ, Suthers IM (1994) Dynamic estuarine plumes and fronts: importance to small fish and plankton in coastal waters of NSW, Australia. *Continental Shelf Research* **14**, 655-672.

Klyashtorin L (1998) Long-term climate change and main commercial fish production in the Atlantic and Pacific. *Fisheries Research* **37**, 115-125.

Klyashtorin LB (2001) 'Climate change and long-term fluctuations of commercial catches - The possibility of forecasting.' FAO, 410, Rome.

Knutson TR, Manabe S (1997) Simulated ENSO in a Global Coupled Ocean–Atmosphere Model: Multidecadal Amplitude Modulation and CO2 Sensitivity. *Journal of Climate* **10**, 138–161.

Knutson TR, Tuleya RE (2004) Impact of CO_2-Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the Choice of Climate Model and Convective Parameterization. *Journal of Climate* **17**, 3477-2495.

Kripalani RH, Kulkarni A, Sabade SS, Khandekar ML (2003) Indian monsoon variability in a global warming scenario. *Natural Hazards* **29**, 189-206.

Kumar KK, Hoerling M, Rajagopalan B (2005) Advancing dynamical prediction of Indian monsoon rainfall. *Geophysical Research Letters* **32**, L08704, doi:10.1029/2004GL021979.

Labitzke K (2004) On the signal of the 11-year sunspot cycle in the stratosphere and its modulation by the quasi-biennial oscillation. *Journal of Atmospheric and Solar-Terrestrial Physics* **66**, 1151-1157.

Lake JS (1967) Rearing experiments with five species of Australian freshwater fishes. I. Inducement to spawning. *Australian Journal of Marine and Freshwater Research* **18**, 137-153.

Latif M, Kleeman R, Eckert C (1997) Greenhouse warming, decadal variability or El Niño? An attempt to understand the anomalous 1990's. *Journal of Climate* **10**, 2221-2239.

Lau KM, Chan PH (1986) The 40-50 Day Oscillation and the El Niño / Southern Oscillation: A new perspective. *Bulletin of the American Meteorological Society* **67**, 533-534.

Lau N, Nath MJ (2000) Impact of ENSO on the variability of the Asian-Australian monsoons as simulated in GCM experiments. *Journal of Climate* **13**, 4287-4309.

Lawrence E, Jackson AR, Jackson JM (1998) 'Longman Dictionary of Environmental Science.' (Harlow, England)

Lee Long WJ, Coles RG, Miller KJ, Vidler KP, Derbyshire KJ (1992) 'Seagrass beds and juvenile prawns and fish nursery grounds.' Department of Primary Industries, QDPI Information Series QI92011, Brisbane.

Lenanton RCJ, Joll LM, Penn JW, Jones K (1991) The influence of the Leeuwin Current on coastal fisheries of Western Australia. *Journal of the Royal Society of Western Australia* **74**, 101-114.

Linacre E (2004) Lake Eo, pand Ep, actual Ea, potential Et and ocean evaporation rates. In 'Pan Evaporation: An example of the detection and attribution of trends in climate variables'. Canberra. (Ed. R Gifford) p. 81. (Australian Academy of Science and the Australian Greenhouse Office)

Livingston RJ (1997) Trophic response of estuarine fishes to long-term changes of river runoff. *Bulletin of Marine Science* **60**, 984-1004.

Lloret J, Lleonart J, Sole I, Fromentin JM (2001) Fluctuations of landings and environmental conditions in the north-western Mediterranean Sea. *Fisheries Oceanography* **10**, 33-50.

Lohmann U, Feichter J (2004) Global indirect aerosol effects: a review. *Atmospheric Chemistry and Physics Discussions* **4**, 7561-7614.

Loneragan NR, Bunn SE (1999) River flows and estuarine ecosystems: Implications for coastal fisheries from a review and a case study of the Logan River, southeast Queensland. *Australian Journal of Ecology* **24**, 431-440.

Lough JM (1998) Recent climate variation on the Great Barrier Reef. In 'State of the Great Barrier Reef World Heritage Area Workshop'. (Eds DR Wachenfeld, JK Oliver and JI Morrissy) pp. 7-20. (Great Barrier Reef Marine Park Authority)

Lough JM (1999) Northeast Australian climate and the changing role of El Niño-Southern oscillation. In '11th Conference on Applied Climatology' pp. 324-326. (American Meteorological Society)

Lough JM (2001) Climate variability and change on the Great Barrier Reef. In 'Oceanographic Processes of Coral Reefs: Physical and Biological Links in the Great Barrier Reef'. (Ed. EJ Wolanski) pp. 269-300. (CRC Press LLC: Boca Raton, Florida)

Lough JM (2005) Observed climate variability and change in the vicinity of the Great Barrier Reef. In 'Rainforest meets Reef: Joint conference of CRC Reef and Rainforest CRC'. Townsville. (Eds L Goggin and T Harvey) p. 122. (CRC Reef Research Centre)

Lunow C, Garrett R, Gribble N, Helmke S, Rose D, Whybird O (2005) 'Fisheries Long Term Monitoring Program - Barramundi survey results from 2000 to 2002.' Department of Primary Industries and Fisheries, Brisbane.

LWA (2005) Scientific Priorities for Australia viewed 2006. http://www.lwa.gov.au/Publications_and_Tools/index.aspx

MacKinnon MR (1986) Rearing and growth of larval and juvenile barramundi *(Lates calcarifer)* in Queensland. In 'Management of wild and cultured Sea Bass/Barramundi *(Lates calcarifer)*'. Darwin, Australia. (Eds J Copland and D Grey) pp. 148-153. (Australian Centre for International Agricultural Research)

Madden RA, Julian PR (1971) Detection of a 40-50 Day Oscillation in the zonal wind in the tropical Pacific. *Journal of the Atmospheric Sciences* **28**, 702-708.

Madden RA, Julian PR (1972) Description of global-scale circulation cells in the tropics with a 40-50 day period. *Journal of the Atmospheric Sciences* **29**, 1109-1132.

Madden RA, Julian PR (1994) Observations of the 40-50 day tropical oscillation - A review. *Monthly Weather Review* **122**, 814-837.

Magro KL, Bibby JM, Gribble NA (1996) 'Tropical Resource Assessment Program - Annual report 1996.' Department of Primary Industries, FRDC Project 95/049, Brisbane.

Magro KL, Gribble NA, Bibby JM (1997) 'Tropical Resource Assessment Program - Annual Report 1997.' Department of Primary Industries, FRDC Project 95/049, Brisbane.

Magro KL, Gribble NA, Bibby JM (1998) 'Tropical Resource Assessment Program - Annual Report 1998.' Department of Primary Industries, FRDC Project 95/049, Brisbane.

Maloney ED, Kiehl JT (2001) MJO-Related SST variations over the tropical Eastern Pacific during northern hemisphere summer. *Journal of Climate* **15**, 675-698.

Manton MJ, McBride JL (1992) Recent research on the Australian monsoon. *Journal of the Meteorological Society of Japan* **70**, 275-285.

Mantua N, Hare SR (2002) The Pacific Decadal Oscillation. *Journal of Oceanography* **58**, 33-44.

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**, 1069-1180.

Marshall GJ (2002) Trends in Antarctic Geopotential Height and Temperature: A Comparison between Radiosonde and NCEP-NCAR Reanalysis Data. *Journal of Climate* **15**, 659-674.

Matthews AJ, Meredith MP (2004) Variability of Antarctic circumpolar transport and the Southern Annular Mode associated with the Madden-Julian Oscillation. *Geophysical Research Letters* **31**, L24312, doi:10.1029/2004GL021666.

May RM (1977) Thresholds and breakpoints in ecosystems with a multiplicity of stable states. *Nature* **269**, 471-477.

Mayle FE, Beerling DJ, Gosling WD, Bush MB (2004) Responses of Amazonian ecosystems to climatic and atmospheric carbon dioxide changes since the last glacial maximum. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* **359**, 499-514.

McBride JL (1987) The Australian summer monsoon. In 'Monsoon Meteorology'. (Eds CP Chang and T Krishnamurti) pp. 203-231. (Oxford University Press: Oxford, England)

McBride JL, Nicholls N (1983) Seasonal relationships between Australian rainfall and the Southern Oscillation. *Monthly Weather Review* **111**, 1998-2004.

McFarlane GA, King JR, Beamish RJ (2000) Have there been recent changes in climate? Ask the fish. *Progress In Oceanography* **47**, 147-169.

McGregor GR, Nieuwolt S (1998) 'Tropical climatology.' (John Wiley & Sons. Ltd.: Chichester, UK)

Meinke H, deVoil P, Hammer GL, Power S, Allan R, Stone RC, Folland C, Potgieter AB (2005) Rainfall Variability at Decadal and Longer Time Scales: Signal or Noise? *Journal of Climate* **18**, 89-96.

Meinke H, Hochman Z (2000) Using seasonal climate forecast to manage dryland crops in northern Australia - Experiences from the 1997-98 seasons. In 'Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems'. (Eds GL Hammer, N Nicholls and C Mitchell) pp. 149-166. (Kluwer Academic Publishers)

Meinke H, Stone RC (2004) Seasonal and inter-annual climate forecasting: the new tool for increasing preparedness to climate variability and change in agricultural planning and operations. *Climatic Change* **In press**.

Mestas-Nuñeza AM, Miller AJ (2006) Interdecadal variability and climate change in the eastern tropical Pacific: A review. *Progress In Oceanography* **69**, 267-284.

Meyers G (1996) Variation of Indonesian throughflow and the El Niño - Southern Oscillation. *Journal of Geophysical Research* **101**, 12,255-12,263.

Meynecke JO, Lee SY, Duke N, Warnken J (2006) Effect of rainfall as a component of climate change on estuarine fish production in Queensland, Australia. *Estuarine, Coastal and Shelf Science* **69**, 491-504.

Micevski T, Franks SW, Kuczera G (2006) Multidecadal variability in coastal eastern Australian flood data. *Journal of Hydrology* **327**, 219-225.

Midgley SH (1987) 'The apparent decline in numbers of some diadromous fish species in northern and east coast areas of Australia, in particular barramundi (*Lates calcarifer*): A review of causes.' Commercial Fisheries Organisation.

Milicich MJ (1994) Dynamic coupling of reef fish replenishment and oceanographic processes. *Marine Ecology Progress Series* **110**, 135-144.

Minns CK, Moore JE (1992) Predicting the impact of climate change on the spatial pattern of freshwater fish yield capability in eastern Canadian lakes. *Climatic Change* **22**, 327-346.

Mishrigi SY (1966) Study of age and growth in *Lates niloticus* (Centropomidae) at Khartoum. *Hydrobiologia* **30**, 43-56.

Mitchell W, Chittleborough J, Ronai B, Lennon GW (2000) Sea level rise in Australia and the Pacific. *The South Pacific Sea Level and Climate Change Newsletter* **Quarterly Newsletter 5**, 10-19.

Moore R (1979) Natural sex inversion in the Giant Perch *(Lates calcarifer)*. *Australian Journal of Marine and Freshwater Research* **30**, 803-813.

Moore R (1982) Spawning and early life history of barramundi, *Lates calcarifer* (Bloch), in Papua New Guinea. *Australian Journal of Marine and Freshwater Research* **33**, 647-661.

Moore R, Reynolds LF (1982) Migration patterns of barramundi, *Lates calcarifer* (Bloch), in Papua New Guinea. *Australian Journal of Marine and Freshwater Research* **33**, 671-682.

Morrissy NM (1985) 'The commercial fishery for barramundi *(Lates calcarifer)* in Western Australia.' Department of Fisheries and Wildlife, 68, Perth, Western Australia.

Moss AJ, Rayment GE, Reilly N, Best EK (1992) 'A preliminary assessment of sediment and nutrient exports from Queensland coastal catchments.' (Queensland Government: Brisbane)

Mulholland PJ, Best GR*, et al.* (1997) Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf of Mexico. *Hydrological Processes* **11**, 949-970.

Munro ISR (1988) Gulf of Carpentaria Prawn Survey, 1963-65. In 'CSIRO at Sea: 50 years of Marine Science'. (Eds V Mawson, DJ Tranter and AF Pearce). (Globe Press: Melbourne)

Murawski SA (1993) Climate change and marine fish distributions: Forecasting from historical analogy. *Transactions of the American Fisheries Society* **122**, 647-658.

Myers R (1998) When Do Environment–recruitment Correlations Work? *Reviews in Fish Biology and Fisheries* **8**, 285-305.

Naujokat B (1986) An update of the observed quasi-biennial oscillation of the stratospheric winds over the tropics. *Journal of Atmospheric Science* **43**, 1873-1877.

Newman M, Compo GP, Alexander MA (2003) ENSO-forced Variability of the Pacific Decadal Oscillation. *Journal of Climate* **16**, 3853-3857.

Nicholls N (1992) Recent performance of a method for forecasting Australian seasonal tropical cyclone activity. *Australian Meteorological Magazine* **40**, 105-110.

Nicholls N (2003) Climate change: are droughts becoming drier and more frequent? In 'Science for Drought'. Brisbane. (Eds R Stone and IJ Partridge) p. 173. (Queensland Department of Primary Industries)

Nicholls N, Kariko A (1993) East Australian rainfall events: Interannual variations, trends and relationships with the Southern Oscillation. *Journal of Climate* **6**, 1141-1152.

Nott J, Hayne M (2001) High frequency of 'super-cyclones' along the Great Barrier Reef over the past 5,000 years. *Nature* **413**, 508-512.

Oliver JE (1981) 'Climatology: Selected applications.' (Edward Arnold: London)

Olsen HF (1983) 'Biological resources of Trinity Inlet and Bay Queensland.' Department of Primary Industries, QB83004, Brisbane, Australia.

Oppenheimer M (1998) Global warming and the stability of the West Antarctic Ice Sheet. *Nature* **393**, 325-332.

Ottersen G, Planque B, Belgrano A, Post E, Reid PC, Stenseth NC (2001) Ecological effects of the North Atlantic Oscillation. *Oecologia* **128**, 1-14.

Pauly D, Pullin SV (1988) Hatching time in spherical, pelagic, marine fish eggs in response to temperature and egg size. *Environmental Biology of Fishes* **22**, 261-271.

Pearce AF (1988) ENSO events, the Leeuwin Current, and larval recruitment of the western rock lobster. *Journal du Conseil International pour l'Éxploration de la Mer* **45**, 13-21.

Pearce M (2000) 'Post stocking survey report: Koombooloomba Dam, Ravenshoe Survey 1, 19 April 2000.' Queensland Department of Primary Industries, QI00095, Brisbane.

Perry AL, Low PJ, Ellis JR, Reynolds JD (2005) Climate change and distribution shifts in marine fishes. *Science* **308**, 1912-1915.

Pittock B (1971) Rainfall and the general circulation. In 'International conference on weather modification'. Canberra pp. 330-338

Pittock B (1973) Global meridional interactions in stratosphere and troposphere. *Quarterly Journal of Royal Meteorological Society* **99**, 424-437.

Platten JR (1996) 'The influence of river freshwater discharge on fishery catch rates in Queensland waters.' Department of Natural Resources, Rockhampton.

Platten JR (1999) 'Historical trends in recreational fishing catches.' Gladstone Area Waterboard, Rockhampton.

Plummer N, Salinger MJ, Nicholls N, Suppiah R, Hennessy KJ, Leighton RM, Trewin B, Page CM, Lough JM (1999) Changes in climate extremes over the Australian region and New Zealand during the twentieth century. In 'Climatic Change'. (Eds TR Karl, N Nicholls and A Ghazi) pp. 183-202. (Kluwer Academic Publishers: Dordrecht)

Power S, Casey T, Folland C, Colman A, Mehta V (1999) Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics* **15**, 319-324.

Power S, Tseitkin F, Mehta V, Lavery B, Torok S, Holbrook N (1999) Decadal climate variability in Australia during the twentieth century. *International Journal of Climatology* **19**.

Primack R, Corlett R (2005) 'Tropical Rain Forests - An ecological and biogeographical comparison.' (Blackwell Publishing)

Puotinen ML, Done TJ, Skelly WC (1997) 'An atlas of tropical cyclones in the Great Barrier Reef Region, 1969-1997.' CRC Reef Research Centre Ltd, Technical Report No. 19, Townsville.

Putten MV, Rassam G (2001) Fisheries, climate change and working together. In 'Fisheries'. pp. 4.

Pyper BJ, Peterman RM (1998) Comparison of methods to account for autocorrelation in correlation analyses of fish data. *Canadian Journal of Fish Aquatic Science* **55**, 2127-2140.

Q.F.B (1937) 'First annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1941) 'Fifth annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1942) 'Sixth annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1943) 'Seventh annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1947) 'Eleventh annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1948) 'Twelfth annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1949) 'Thirteenth annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1950) 'Fourteenth annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1955) 'Nineteenth annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1956) 'Twentieth annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1957) 'Twenty-first annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1959) 'Twenty-third annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1962) 'Twenty-sixth annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1963) 'Twenty-seventh annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1964) 'Twenty-eighth annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1966) 'Thirtieth annual report of the Fish Board.' Fish Board, Brisbane.

Q.F.B (1973) 'First annual report of the Queensland Fish Board.' Queensland Fish Board, Brisbane.

Q.F.M.A. (1994) 'Spawning zones introduced for the east coast barramundi fishery.' Queensland Fish Management Authority, Brisbane.

Quinn RH, Garrett R (1992) The fisheries resources of the Fitzroy region. In 'Fitzroy Catchment Symposium'. Rockhampton. (Eds LJ Duivenvoorden, DF Yule, LE Fairweather and AG Lawrie) pp. 1-17. (University of Central Queensland)

Reynolds LF, Moore R (1973) 'Barramundi *(Lates calcarifer)* research in Papuan waters. Annual Report.' Department of Agriculture, Stock and Fisheries, Port Moresby.

Reynolds LF, Moore R (1982) Growth rates of barramundi, *Lates calcarifer* (Bloch), in Papua New Guinea. *Australian Journal of Marine and Freshwater Research* **33**, 663-670.

Risbey J, Karoly D, Reynolds A, Braganza K (2003) Drought and climate change. In 'Science for Drought'. Brisbane. (Eds R Stone and IJ Partridge) p. 173. (Queensland Department of Primary Industries)

Robins JB, Halliday IA, Staunton-Smith J, Mayer DG, Sellin MJ (2005) Freshwater flow requirements of estuarine fisheries in tropical Australia: a review of the state of knowledge and application of a suggested approach. *Marine and Freshwater Research* **56**, 343-360.

Robins JB, Mayer DG, Staunton-Smith J, Halliday IA, Sawynok B, Sellin MJ (2006) Variable growth rates of a tropical estuarine fish species (barramundi, *Lates calcarifer* Bloch) under different freshwater flow conditions. *Journal of Fish Biology* **69**, 379-391.

Roderick ML, Farquhar GD (2004) Changes in Australian pan evaporation from 1970 - 2002. *International Journal of Climatology* **24**, 1077-1090.

Rohan G, Griffin RK, Grey DL (1981) 'Northern Territory barramundi fishery. Review of management - situation paper.' Department of Primary Production, Darwin.

Rosenzweig C, Hillel D (1998) 'Climate change and the global harvest.' (Oxford University Press Inc.: New York)

Rozas LP, Hackney CT (1983) The importance of oligohaline estuarine wetland habitats to fisheries resources. *Wetlands* **3**, 77-89.

Russell DJ (1988) 'An assessment of the east Queensland inshore gill net fishery.' Queensland Department of Primary Industries, Information Series QI88024., Brisbane, Australia.

Russell DJ, Garrett RN (1983) Use by juvenile barramundi, *Lates calcarifer* (Bloch), and other fishes of temporary supralittoral habitats in a tropical estuary in northern Australia. *Australian Journal of Marine and Freshwater Research* **34**, 805-811.

Russell DJ, Garrett RN (1985) Early life history of barramundi, *Lates calcarifer* (Bloch), in north-eastern Queensland. *Australian Journal of Marine and Freshwater Research* **36**, 191-201.

Russell DJ, Garrett RN (1988) Movements of juvenile barramundi, *Lates calcarifer* (Bloch), in North-Eastern Queensland. *Australian Journal of Marine and Freshwater Research* **39**, 117-123.

Russell DJ, Hales P (1993) 'A survey of the Princess Charlotte Bay recreational barramundi fishery.' Queensland Department of Primary Industries, QI93049, Brisbane.

Russell DJ, Hales P, Helmke SA (1996) 'Stream habitat and fish resources in the Russell and Mulgrave rivers catchment.' Department of Primary Industries, Cairns.

Rutledge WP (1990) 'Barramundi (*Lates calcarifer*, Bloch) aquaculture and recreational stocking in Queensland.' Queensland Department of Primary Industries, QI90035, Brisbane.

Salby M, Callaghan P (2000) Connection between the solar cycle and the QBO: The missing link. *Journal of Climate* **13**, 2652-2662.

Salen-Picard C, Darnaude AM, Arlhac D, Harmelin-Vivien ML (2002) Fluctuations of macrobenthic populations: a link between climate-driven river run-off and sole fishery yields in the Gulf of Lions. *Oecologia* **133**, 380-388.

Salinger MJ, Stigter CJ, Das HP (2000) Agrometeorological adaptation strategies to increasing climate variability and climate change. *Agricultural and Forest Meteorology* **103**, 167-184.

Sánchez-Velasco L, Avalos-García C, Rentería-Cano M, Shirasago B (2004) Fish larvae abundance and distribution in the central Gulf of California during strong environmental changes (1997–1998 El Niño and 1998–1999 La Niña). *Deep Sea Research Part II: Topical Studies in Oceanography* **51**, 711-722.

Sanchez-Velasco L, Valdez-Holguin JE, Shirasago B, Cisneros-Mata MA, Zarate A (2002) Changes in the Spawning Environment of *Sardinops caeruleus* in the Gulf of California during El Niño 1997-1998. *Estuarine, Coastal and Shelf Science* **54**, 207-217.

Sandweiss DH, Maasch KA, Chai F, Andrus CFT, Reitz EJ (2004) Geoarchaeological evidence for multidecadal natural climatic variability and ancient Peruvian fisheries. *Quaternary Research* **61**, 330-334.

Sarmiento JL, Slater R*, et al.* (2004) Response of ocean ecosystems to climate warming. *Global Biogeochemical cycles* **18**, GB3003, doi:10.1029/2003GB002134.

Sawynok B (1998) 'Fitzroy river effects of freshwater flows on fish.' InfoFish Services, Rockhampton.

Schaefer MB (1954) Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Inter-American Tropical Tuna Commissison Bulletin* **1**, 27-56.

Scheffer M, Carpenter S, Foley JA, Folke C, Walker B (2001) Catastrophic shifts in ecosystems. *Nature* **413**, 591-596.

Schipp G (1996) 'Barramundi farming in the Northern Territory.' Department of Primary Industries and Fisheries, Darwin, Australia.

Shaklee JB, Salini JP (1985) Genetic variation and population subdivision in Australian barramundi, *Lates calcarifer* (Bloch). *Australian Journal of Marine and Freshwater Research* **36**, 203-218.

Shaklee JB, Salini JP, Garrett RN (1993) Electrophoretic characterization of multiple genetic stocks of barramundi perch in Queensland, Australia. *Transactions of the American Fisheries Society* **122**, 685.

Shapiro SS, Wilk MB, Chen HJ (1968) A comparative study of various tests of normality. *Journal of the American Statistical Association* **63**, 1343-1372.

Sheaves M (2005) The road to ecosystem collapse. In 'Research for Coastal Management - Coastal CRC conference'. Coolangatta, Queensland p. 60. (CRC for Coastal Zone Estuary and Waterway Management)

Sheridan P (1996) Forecasting the fishery for pink shrimp, *Penaeus duorarum*, on the Tortugas Grounds, Florida. *Fishery Bulletin* **94**, 743-755.

Simmonds I, Hope P (1997) Persistence characteristics of Australian rainfall anomalies. *International Journal of Climatology* **17**, 597-613.

Smith I (2004) An assessment of recent trends in Australian rainfall. *Australian Meteorological Magazine* **53**, 163-173.

Sobrino I, Silva L, Bellido JM, Ramos F (2002) Rainfall, river discharge and sea temperatures as factors affecting abundance of two coastal benthic cephalopod species in the Gulf of Cadiz (SW Spain). *Bulletin of Marine Science* **71**, 851-865.

Solow AR (2002) Fisheries recruitment and the North Atlantic Oscillation. *Fisheries Research* **54**, 295-297.

Stanhill G (2004) Global dimming: historic evidence and possible causes. In 'Pan Evaporation: An example of the detection and attribution of trends in climate variables'. Canberra. (Ed. R Gifford) pp. 43-45. (Australian Academy of Science and the Australian Greenhouse Office)

StatSoft. Inc. (2005) STATISTICA (data analysis software system). In.

Staunton-Smith J, Robins JB, Sellin MJ, Halliday IA, Mayer DG (2004) Does the timing of freshwater flowing into a dry tropical estuary affect year-class strength of barramundi (*Lates calcarifer*)? *Marine and Freshwater Research* **55**, 787-797.

Steffen W (2006) 'Stronger Evidence but New Challenges: Climate Change Science 2001-2005.' Australian Greenhouse Office, Canberra.

Stergiou KI, Christou ED (1996) Modelling and forecasting annual fisheries catches: comparison of regression, univariate and multivariate time series methods. *Fisheries Research* **25**, 105-138.

Stone R (1994) Adapting climate information for the benefit of agriculture in Australia. *Agricultural Systems and Information Technology* **6**, 34.

Sturman AP, Tapper NJ (1996) 'The weather and climate of Australia and New Zealand.' (Oxford University Press)

Sturman AP, Tapper NJ (2006) 'The weather and climate of Australia and New Zealand.' (Oxford University Press)

Suppiah R, Hennessy KJ (1998) Trends in total rainfall, heavy-rain events and number of dry days in Australia, 1910-1990. *International Journal of Climatology* **10**, 1141-1164.

Sutcliffe Jr WH (1973) Correlations between seasonal river discharge and local landings of American lobster (*Homarus americanus*) and Altantic halibut (*Hippoglossus hippoglossus*) in the Gulf of St. Lawrence. *Journal Fisheries Research Board of Canada* **30**, 856-859.

Sutcliffe Jr WH, Drinkwater K, Muir BS (1976) Correlations of fish catch and environmental factors in the Gulf of Maine. *Journal of Fisheries Research Board Canada* **34**, 19-30.

Thompson DWJ, Lorenz DJ (2004) The signature of the annular mode in the tropical troposphere. *Journal of Climate* **17**, 4330–4342.

Thompson DWJ, Wallace JM (2000) Annular Modes in the Extratropical Circulation. Part I: Month-to-Month Variability. *Journal of Climate* **13**, 1000-1016.

Thresher R (1994) Climate cycles may help explain fish recruitment in south-east Australia. In 'Australian Fisheries'.

Thresher R (2002) Solar correlates of Southern Hemisphere mid-latitude climate variability. *International Journal of Climatology* **22**, 901-915.

Troup AJ (1961) Variations in upper tropospheric flow associated with the onset of the Australian summer monsoon. *Indian Journal of Meteorology and Geophysics* **12**, 217-229.

Troup AJ (1965) The 'southern oscillation'. *Quarterly Journal of Royal Meteorological Society* **91**, 490-506.

Tsonis AA, Elsner JB, Hunt AG, Jagger TH (2005) Unfolding the relation between global temperature and ENSO. *Geophysical Research Letters* **32**, L09701, doi:10.1029/2005GL022875.

Vance DJ, Haywood MDE, Heales DS, Kenyon RA, Loneragan NR (1998) Seasonal and annual variation in abundance of postlarval and juvenile banana prawns *Penaeus merguiensis* and environmental variation in two estuaries in tropical northeastern Australia: a six year study. *Marine Ecology Progess Series* **163**, 21-36.

Vance DJ, Staples DJ, Kerr JD (1985) Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus merguiensis*) in the Gulf of Carpentaria, Australia. *Journal du Conseil International pour L'Exploration de la Mer* **42**, 83-97.

Vecchi GA, Soden BJ, Wittenberg At, Held IM, Leetmaa A, Harrison MJ (2006) Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature* **441**, 73-76.

Venegas SA (2003) The Antarctic Circumpolar Wave: A combination of two signals? *Journal of Climate* **16**, 2509-2525.

Visbeck M, Hall A (2004) Interannual southern hemispheric atmospheric variability in the NCEP reanalysis between 1980 and 2002. *Journal of Climate* **17**, 2255-2258.

Wachenfeld DR, Oliver JK, Morrissy JI (Eds) (1998) 'State of the Great Barrier Reef World Heritage Area.' (Great Barrier Reef Marine Park Authority)

Walsh KJE, Cai W, Hennessy KJ, Jones R, McInnes K, Nguyen K, Page CM, Whetton P (2002) 'Climate change in Queensland under enhanced greenhouse conditions.' CSIRO, Aspendale.

Walsh KJE, Hennessy KJ, Jones R, McInnes K, Page CM, Suppiah R, Whetton P (2001) 'Climate change in Queensland under enhanced greenhouse conditions: Third annual report, 1999-2000.' CSIRO.

Walsh KJE, Ryan BF (2000) Tropical cyclone intensity increase near Australia as a result of climate change. *Journal of Climate* **13**, 3029-3036.

Wheeler MC, Hendon HH (2004) An All-Season Real-Time Multivariate MJO Index: Development of an Index for
Monitoring and Prediction. *American Meteorological Society* **132**, 1917-1932.

Whetton P (2003) Projected future climate change for Australia. In 'Climate Impacts on Australia's Natural Resources: Current and Future Challenges'. Gold Coast pp. 12-14. (The Standing Committee on Natural Resources Management)

Whetton P, McInnes K, Jones RN, Hennessy KJ, Suppiah R, Page CM, Bathols J, Durack PJ (2005) 'Australian climate change projections for impact assessment and policy application: a review.' CSIRO Marine and Atmospheric Research, Aspendale.

White ME, Downton MW (1991) The shrimp fishery in the Gulf of Mexico: relation to climatic variability and global atmospheric patterns. In 'Teleconnections linking worldwide climate anomalies: scientific basis and societal impacts'. (Eds MH Glantz, RW Katz and N Nicholls) pp. 459-491. (Cambridge University Press: Cambridge)

White WB (2000) Influence of the Antarctic Circumpolar Wave on Australian precipitation from 1958-1997. *Journal of Climate* **13**, 2125-2141.

Wild M (2004) Recent evidence on changes in surface solar radiation. In 'Pan Evaporation: An example of the detection and attribution of trends in climate variables'.

Canberra. (Ed. R Gifford) pp. 46-49. (Australian Academy of Science and the Australian Greenhouse Office)

Wilkes DS (1995) 'Statistical Methods in Atmospheric Science.' (Academic Press: San Diego, California)

Williams LE (1997) 'Queensland's Fisheries Resources: Current condition and recent trends 1988-1995.' Queensland Department of Primary Industries, QI97007, Brisbane.

Williams LE (2002) 'Queensland's Fisheries Resources: Current condition and recent trends 1988-2000.' Queensland Department of Primary Industries, QI02012, Brisbane.

Wood CM (1997) Global warming: Implications for freshwater and marine fish. *The society for experimental biology seminar series* **61**, 440.

Woodroffe CD (1993) Late Quaternary evolution of coastal and lowland riverine plains of southeast Asia and northern Australia: an overview. *Sedimentary Geology* **83**, 163-175.

Young JW, Bradford RW, Lamb TD, Clementson LA, Kloser R, Galea H (2001) Yellowfin tuna (*Thunnus albacares*) aggregations along the shelf break off south-eastern Australia: links between inshore and offshore processes. *Marine and Freshwater Research* **52**, 463-474.

Zhang XG, Casey TM (1992) Long-term variations in the Southern Oscillation and relationships with Australian rainfall. *Australian Meteorological Magazine* **40**, 211-225.

Zhang Y, Wallace JM, Battisti DS (1997) ENSO-like interdecadal variability: 1900-93. *Journal of Climate* **10**, 1004-1020.

APPENDICES (On attached CD)

APPENDIX 1:	**Summary of reviewed studies overseas**
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APPENDIX 1 Summary of reviewed studies which explore the links between climate and inshore fisheries overseas sorted by region and year of publication. SSTs= Sea surface temperatures.

Location	Author	Year	Species	Key Findings
USA, Gulf of Maine	(Sutcliffe Jr)	1976	Alewife *Alosa pseudoharengus*	New England catch from 1928-1971 and Saint Andrews SSTs for the month of April with a lag of six years (*r*=0.850).
			Butterfish *Peprilus triancanthus*	New England catch from 1928-1971 and Saint Andrews SSTs (April and May) lagged by four years (*r*=0.735).
			Atlantic Cod *Gadus morhua*	Cod catch from the Northwest Atlantic fisheries sub-area 5 negatively correlates with St Andrews July and August SSTs from 1921-1973 with a four year lag (*r*=-0.833).
			Atlantic Herring *Clupea harengus harengus*	Plots of New England herring catch and St Andrews SSTs in November (1928-1971) with a two year lag (*r*=0.604).
			Atlantic Menhaden *Brevoortia tyrannus*	New England menhaden landings are correlated with St. Andrews SSTs (1929-1971) in April (*r*=0.872) with a three year lag.
			Redfish *Sebastes marinus*	Redfish catch from the Northwest Atlantic fisheries sub-area 5 and St. Andrews SSTs (1936-1973) are negatively correlated (*r*=-0.728) with an eight year lag.
			Silver Hake *Merluccius bilinearis*	New England catch correlates negatively with a five year lag with St. Andrews SSTs (1928-1971) (*r*=0.781).
			Striped Bass *Morone saxatilis*	New England bass catch with Boothbay Harbour SSTs in August (1930-1971) with a three year lag (*r*=-0.644).
			Yellow tail flounder *Limanda ferruginea*	Yellow tail flounder catch from the Northwest Atlantic fisheries sub-area 5 negatively correlated with August St. Andrews SSTs (1935-1974) with a two year lag (*r*=-0.792).
			Hard Clams *Mercenaria mercenaria*	New England commercial clam catch correlated with St Andrews SSTs lagged by two years (*r*=0.805).
			Soft Shelled clams *Mya arenaria*	New England clam catch negatively correlated with St Andrews SSTs in November and December (1928-1971) and a seven year lag (*r*=-0.798).
			Sea Scallops *Plactopecten magellanicus*	New England catch with St Andrews SSTs (1928-1971) in November with a six year lag (*r*=0.796).
USA, Florida	(Sheridan)	1996	Pink Shrimp *Penaeus duorarum*	Development and testing of a range of forecast models using streamflow and ground water level in wells (R^2 up to 0.911) to predict *P. duorarum* catch with forecasts within ± 20% of actual landings.
	(Livingston)	1997	Various estuarine fisheries (number and biomass)	Correlation with seasonal interannual variations of Apalachicola river flow indicate that the highest fish biomass recorded followed peak flow events and lowest species richness after drought periods.

Location	Author	Year	Species	Key Findings
USA, Oregon, California, Alaska	(Fisher and Pearcy)	1988	Coho Salmon *Oncorhynchus kisutch*	Decreased survival of juveniles related to decreased upwelling and therefore reduced primary production and probable increased predation.
	(Mantua, Hare *et al.*)	1997	Chinook, Sockeye and pink salmon	Changes in the mean catch of –64.4% to +251.9% in response to reversals in the Pacific Interdecadal Oscillation.
USA, Texas	(Gunter and Hilderbrand)	1954	White Shrimp *Penaeus setiferus*	Annual catch and three year running average of Texas state rainfall in the same year and 2 previous years significantly correlated (*r*=0.804) year 1927-1952.
USA, North-east	(Summers)	1987	Striped bass *Morone saxatilis*	Time series models indicated that hydrographic factors dominate striped bass dynamics in all three estuaries considered (Potomac, Delaware, and Hudson).
Canada	(Drinkwater and Myers)	1987	Cod *Gadus morhua*	Correlations with mean monthly river discharge and coastal sea surface temperature explain 65% of landings when lagged by the approximate age of recruitment.
Gulf of Mexico	(White and Downton)	1991	Brown shrimp *Penaeus aztecus*	Spring and winter discharge the most important variable in summer brown shrimp landing.
			White shrimp *Penaeus setiferus*	Total catch of white shrimp negatively correlated with SST, air temperature and wind vector in winter but positively correlated with summer SSTs and river discharge into the gulf.
Canada, Vancouver	(Perry, Boutillier *et al.*)	2000	Smooth pink shrimp *Pandalus jordani*	Multiple regression analysis to predict CPUE of shrimp using wind stress, tidal current speed, SST, salinity and hours of bright sunshine explained 44% of the variation in otter-trawl data and 35% of beam-trawl variability.
Canada, Quebec	(Sutcliffe Jr)	1973	American lobster *Homarus americanus*	Significant correlation (*r*=0.831) between April St. Lawrence River runoff and annual total catch (9 year lag).
			Halibut *Hippoglossus hippoglossus*	March runoff correlated significantly with annual total catch lagged by ten years (*r*=0.855).
New Zealand	(Scott and Pankhurst)	1992	New Zealand Snapper *Pagrus auratus*	Spawning onset varied by up to three weeks dependant on SSTs in October.
	(Francis, Langley *et al.*)	1996	New Zealand snapper *Pagrus auratus*	Significant correlation between snapper 1+ class and mean April-June sea surface temperatures during the 0+ year (*r*=0.97).
India	(Murty and Edelman)	1971	Indian oil sardine *Sardinella longiceps*	The long-term fluctuations of the Indian oil sardine fishery related to the strength of the summer monsoon over the Peninsular region of India.
	(Bardach and Santerre)	1981	Indian Oil Sardine *Sardinella longiceps*	Spawning triggered by water temperature decreases at the start of the monsoon.
India, Bay of Bengal	(Pati)	1984	Various species	A significant correlation between the fluctuations in total annual southwest monsoon rainfall and total drift-gillnet catch rate (*r*=0.847) and plankton feeders (*r*=0.79) in a fishery.
Mosambique	(Jorge da Silva)	1986	Shallow water shrimp *Penaeus indicus*	Zambezi outflow influences the recruitment strength of the shrimp either by directly affecting the number of recruits or by inducing changes in the size at migration (or a combination of both).

Location	Author	Year	Species	Key Findings
China	(Kim, Kang *et al.*)	2005	Anchovy *Engraulis japonicus* Hairtail *Trichiurus lepturus*	Influences from ENSO affecting the flow from the Yangtze River affected the spatial distribution of the early life stages of both Anchovy and Hairtail by affecting the productivity of spawning grounds and the extent of nursery habitats in the East China Sea.
Chile	(Castro, Salinas *et al.*)	2000	Anchovy *Engraulis ringens*	Timing and location of spawning affected by a number of environmental factors including upwelling, winds, downwelling, river plumes, temperature and turbulence. Growth rates and egg mortality affected by oceanographic temperature conditions generated by wind switches.
Global	(Klyashtorin)	2001	Various commercial fisheries	Long-term simultaneous oscillations in the total catch of Atlantic and Pacific herring, Atlantic cod, European, South American, Peruvian, Japanese and Californian sardine, South African and Peruvian anchovy, Pacific salmon, Alaska Pollock, Chilean jack mackerel and some other species are closely correlated with the Atmospheric Circulation Index.
Mediterranean North-west	(Lloret, Lleonart *et al.*)	2001	Thirteen commercial species	Significant positive correlation between monthly catch and CPUE and local river run-off and wind mixing index during the spawning season, with time lags of less than one year.
Mediterranean Gulf of Lions	(Salen-Picard, Darnaude *et al.*)	2002	Sole *Solea solea*	Positive correlation between mean annual discharge of the Rhone river and annual commercial landings of sole five years later.
Spain, Gulf of Cadiz	(Sobrino, Silva *et al.*).	2002	Octopus *Octopus vulgaris* Cuttlefish *Sepia officinalis*	Correlations between octopus landings and rainfall, SSTs and river flows were all significant.

REFERENCES:

Bardach JE, Santerre RM (1981) Climate and the fish in the sea. *BioScience* **31**, 206-215.

Castro LR, Salinas GR, Hernandez EH (2000) Environmental influences on winter spawning of the anchoveta *Engraulis ringens* off central Chile. *Marine Ecology Progess Series* **197**, 247-258.

Drinkwater KF, Myers RA (1987) Testing predictions of marine fish and shellfish landings from environmental variables. *Canadian Journal of Fisheries and Aquatic Sciences* **44**, 1568-1573.

Fisher JP, Pearcy WG (1988) Growth of juvenile Coho Salmon *(Oncorhynchus kisutch)* off Oregon and Washington, USA, in years of differing coastal upwelling. *Canadian Journal of Fisheries and Aquatic Sciences* **45**, 1036-1044.

Francis MP, Langley AD, Gilbert DJ (1996) Prediction of snapper (*Pagrus auratus*) recruitment from sea surface temperature. In 'Developing and sustaining world fisheries resources. 2nd World Fisheries Congress - The state of science and management'. Brisbane, Australia. (Eds DA Hancock, DC Smith, A Grant and JP Beumer) pp. 67-71. (CSIRO).

Gunter G, Hilderbrand HH (1954) The relation of total rainfall of the state and catch of the marine shrimp (*Penaeus setiferus*) in Texas waters. *Bulletin of the Marine Science of the Gulf and Caribbean* **4**, 95-103.

Jorge da Silva A (1986) 'River runoff and shrimp abundance in a tropical coastal ecosystem - the example of the Sofala Bank (Central Mozambique).' NATO ASI Series, Springer-Verlag: Heidelberg

Kim J-Y, Kang Y-S, Oh H-j, Suh Y-S, Hwang J-D (2005) Spatial distribution of early life stages of anchovy (*Engraulis japonicus*) and hairtail (*Trichiurus lepturus*) and their relationship with oceanographic features of the East China Sea during the 1997 –1998 El Niño Event. *Estuarine, Coastal and Shelf Science* **63**, 13-21.

Klyashtorin LB (2001) 'Climate change and long-term fluctuations of commercial catches - The possibility of forecasting.' FAO, 410, Rome.

Livingston RJ (1997) Trophic response of estuarine fishes to long-term changes of river runoff. *Bulletin of Marine Science* **60**, 984-1004.

Lloret J, Lleonart J, Sole I, Fromentin JM (2001) Fluctuations of landings and environmental conditions in the north-western Mediterranean Sea. *Fisheries Oceanography* **10**, 33-50.

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**, 1069-1180.

Murty AVS, Edelman MS (1971) On the relation between the intensity of the south-west monsoon and the oil-sardine fishery of India. *Indian Journal of Fisheries* **13**, 142-149.

Pati S (1984) Observations on the relation between rainfall and the inshore fishery along the Orissa coast. *Journal du Conseil International pour L'Exploration de la Mer* **41**, 145-148.

Perry RI, Boutillier JA, Foreman GG (2000) Environmental influences on the availability of smooth pink shrimp, *Pandalus jordani*, to commercial fishing gear off Vancouver Island, Canada. *Fisheries Oceanography* **9**, 50-61.

Salen-Picard C, Darnaude AM, Arlhac D, Harmelin-Vivien ML (2002) Fluctuations of macrobenthic populations: a link between climate-driven river run-off and sole fishery yields in the Gulf of Lions. *Oecologia* **133**, 380-388.

Scott SG, Pankhurst NW (1992) Interannual variation in the reproductive cycle of the New Zealand snapper *Pagrus auratus* (Bloch & Schneider) (Sparidae). *Journal of Fish Biology* **41**, 685-696.

Sheridan P (1996) Forecasting the fishery for pink shrimp, *Penaeus duorarum*, on the Tortugas Grounds, Florida. *Fishery Bulletin* **94**, 743-755.

Sobrino I, Silva L, Bellido JM, Ramos F (2002) Rainfall, river discharge and sea temperatures as factors affecting abundance of two coastal benthic cephalopod species in the Gulf of Cadiz (SW Spain). *Bulletin of Marine Science* **71**, 851-865.

Summers JK (1987) The role of interactions among environmental conditions in controlling historical fisheries variability. *Estuaries* **10**, 255-266.

Sutcliffe Jr WH (1973) Correlations between seasonal river discharge and local landings of American lobster (*Homarus americanus*) and Altantic halibut (*Hippoglossus hippoglossus*) in the Gulf of St. Lawrence. *Journal Fisheries Research Board of Canada* **30**, 856-859.

White ME, Downton MW (1991) The shrimp fishery in the Gulf of Mexico: relation to climatic variability and global atmospheric patterns. In 'Teleconnections linking worldwide climate anomalies: scientific basis and societal impacts'. (Eds MH Glantz, RW Katz and N Nicholls) pp. 459-491. (Cambridge University Press: Cambridge)

APPENDIX 2 Summary of reviewed studies which explore the links between climate and inshore fisheries in Australia sorted by region and year of publication sorted by region and year of publication. CPUE= Catch per unit effort; ENSO = El Niño/Southern Oscillation; SOI = Southern Oscillation Index; SSTs = Sea surface temperatures; ZWW = Zonal westerly winds. Lag effects are indicated by a superscript (e.g. Rainfall^{-3} represents a correlation with rainfall three years prior).

Site	Author	Year	Species	Key Findings
QLD	(Dunstan)	1959	Barramundi *Lates calcarifer*	Abundance of barramundi appears to be closely associated with the flow of fresh water on the east coast.
	(Stephenson and Williams)	1981	Penaeid prawns Various species	Highest correlation with catch was temperature of inshore water at varying optimum lag periods depending on species. Rainfall at some previous optimal time lag increased catch.
	(Dredge)	1985	Banana prawn *Penaeus merguiensis*	The life cycle of the prawn appears to vary depending on local environmental conditions.
	(Platten)	1996	Recreational and commercial fisheries	Significant positive correlation between catch rate (CPUE) and Fitzroy River flow (r=0.707).
	(Sawynok)	1998	Barramundi *Lates calcarifer*	Positive correlation between recruitment of barramundi and river flows or rainfall from October to February with strong recruitment evident in years of high flows where flow was greater than 1.4 Ml from December to February. Early flows in October or November not related to spawning. Growth curves indicate higher growth in higher flow rates, lower growth with low flow. Higher movement of individuals during periods of high flow.
	(Sheaves)	1998	Various species	Estuarine fish assemblages affected by variations in salinity but not by temperature or turbidity.
	(Platten)	1999	Recreational catch	Recreational catch at Gladstone harbour correlates significantly with total outflow of the Calliope and Boyne Rivers (R^2=0.988).
	(Limpus and Nicholls)	2000	Green Turtles *Chelonia mydas*	Significant correlation between mean May-October SOI two years prior and the number of breeding female turtles recorded on Heron Island (R^2=0.50) and Raine Island (R^2=0.42).
	(Meager, Vance *et al.*)	2003	Banana prawn *Penaeus merguiensis*	Post-larvae numbers, temperature and rainfall explained 23% of variation in juvenile catch. Temperature and rainfall explained some variation in post-larval catch (9.9%).
	(Staunton-Smith, Robins *et al.*)	2004	Barramundi *Lates calcarifer*	Position correlation between the abundance of year classes and quantity of fresh water flowing into the estuary during spring and summer.
	(Robins, Halliday *et al.*)	2005	Mud crab *Syclla serrata*	Multiple regression models including autumn flow and annual rainfall^{-3} explained 54.2% of variation in the catch and effort relationship.
			Banana prawn *Penaeus merguiensis*	Multiple regression models of freshwater flow and local rainfall accounted for 49.3% of variation in catch and effort relationship residuals.
			Barramundi *Lates calcarifer*	44.0% of variation in catch and year relationship residuals explained by multiple regression model of annual flow^{-2}, annual rain^{-2} and autumn flow^{-2}.
	(Meynecke, Lee *et al.*)	2006	Barramundi *Lates calcarifer*	Up to 30% of variation in Queensland's total fish catch and up to 80% of the barramundi catch for specific regions can be explained by rainfall.
	(Robins, Mayer *et al.*)	2006	Barramundi *Lates calcarifer*	Growth rates of fish were significantly and positively correlated to freshwater flowing into the estuary.

Site	Author	Year	Species	Key Findings
GBR	(Isdale)	1984	Massive corals *Porites species*	Timing, width and intensity of florescent bands correlated significantly with summer, monsoonal rainfall and coastal run-off (R^2=0.80) with Burdekin River discharge – no lag.
	(Lough and Barnes)	1990	Corals *Porites solida*	Annual maximum coral density significantly negatively correlated with cloud coverage and rainfall and significantly positively correlated with temperature in summer. Minimum density correlated with rainfall, cloud coverage and pressure in autumn and SOI in autumn/winter/spring.
	(Milicich)	1994	Various reef fish species	Positive correlation between inter-annual changes in frequency of onshore winds and larval supply.
	(Isdale, Stewart *et al.*)	1998	Massive corals *Porites species*	Summer (October – March) rainfall and the instrumental florescent series from coral cores correlated (r=0.65).
GOC	(Davis)	1985	Barramundi *Lates calcarifer*	Variations in salinity and connectivity to saline environments and hence spawning success and survival of small juveniles affected by timing, intensity and duration of the monsoon wet season.
	(Staples)	1985	Banana prawn *Penaeus merguiensis*	Summer monsoonal rainfall and following autumn catch of prawns in the Karumba region significantly correlated (r=0.864).
	(Vance, Staples *et al.*)	1985	Banana prawn *Penaeus merguiensis*	Significant correlation between commercial catch at Karumba and summer river discharge (r =0.80). Winter temperatures (air) have a positive correlation with catch for Mornington Island (r=0.83) and Groote Island (r=0.76). Summer air temperatures significantly negatively correlate with catch in Karumba (r=-0.69) Forward selection multiple regression explained 67% to 95% of catch using rainfall and summer spring onshore winds as environmental variables.
	(Staples and Vance)	1986	Banana prawn *Penaeus merguiensis*	Monthly rainfall during the monsoon accounted for 74% of the observed monthly emigration rate out of rivers and into estuarine areas (r=0.859). 40% of observed variation in catch related to tide height. Correlation between commercial catch and rainfall significant (r=0.85) over thirteen years of study.
		1987	Banana prawn *Penaeus merguiensis*	Multiple regression analysis conducted between prawn catch in five rivers with tide and rainfall data, (r =0.76) with rainfall and Smithburn River catch.
	(Vance, Haywood *et al.*)	1996	Tiger prawn *Penaeus semisulcatus*	Rainfall the most important environmental variable in affecting abundance of post-larvae prawns in the seagrass beds in the Embly River.
	(Vance, Haywood *et al.*)	1998	Banana prawn *Penaeus merguiensis*	Significant negative correlation between wet season rainfall and emigration of juvenile prawns from the Embly and Mission Rivers (r=-0.85), tidal range (r=0.83) and temperature in the river pre-wet (r=0.76).
	(Catchpole and Auliciems)	1999	Banana prawn *Penaeus merguiensis* Tiger prawn *Penaeus semisulcatus* *Penaeus esculentus*	Significant positive correlation between monthly SOI for August – April and total annual catch of *P. merguiensis*. Significant negative correlation between monthly SOI for August – December and total annual catch residuals of *P. semisulcatus* and August – April for *P. esculentus.*
	(Vance, Bishop *et al.*)	2003	Banana prawn *Penaeus merguiensis*	Results similar to those of Vance *et a*l, 1985. Rainfall is still the most significant variable in the models of commercial catch variation in the south-eastern Gulf (r=0.83 at Karumba) but not as important in the northern and western regions (r=0.36 at Weipa). Temperature also significant for some areas e.g. November – February temperature explained 82% of catch at Mornington) and wind for others (September – November wind explained 28% of catch at Weipa).

Site	Author	Year	Species	Key Findings
NSW	(Ruello)	1973	School Prawn *Metapenaeus macleayi*	Increasing freshwater flow increases seaward migration of *M. macleayi* enhancing reproductive potential and recruitment. Significant correlation between rainfall and catch in the following year (*r*=0.642).
	(Glaister)	1978	School prawn *Metapenaeus macleayi*	Schooling of juveniles showed a lunar periodicity peaking five days after a full moon. Significant correlation (*r*=0.64) between monthly production and total monthly discharge of Clarence River in the previous month.
WA	(Penn and Caputi)	1986	Tiger prawn *Penaeus semisulcatus*	Inclusion of rainfall as a measure of cyclone activity increased the proportion of catch explained by a Ricker stock recruitment curve from 42% to 94%.
	(Loneragan, Potter *et al.*)	1987	Various indicator species	The number of species, abundance and biomass of fish in the Peel-Harvey estuary system rivers rose with increases in the salinity and temperature of the surface and bottom of the water column.
	(Pearce)	1988	Western rock lobster *Panulirus cygnus*	Lobster settlement affected by sea level fluctuations driven by ENSO (*r*=0.73).
	(Lenanton, Joll *et al.*)	1991	Saucer scallop Amusium balloti	Negative relationship between recruitment of scallop in Shark Bay and the strength of the Leeuwin current.
			Western King Prawn *Peneaus latisulcatus*	Significant positive relationship between Leeuwin current (mean monthly Freemantle sea level) and recruitment of prawns in shark bay (*r*=0.60).
			Pilchards *Sardinops neopilchardus*	The Leeuwin Current significantly reduces the production of pilchards in the Albany region.
	(Caputi and Brown)	1993	Western Rock Lobster *Panulirus cygnus*	Significant correlations between winter/spring storms as measured by Oct-Nov rainfall and Freemantle sea level with juvenile lobster settlement (R^2=0.68).Environmental variables are the main cause of the fluctuations in lobster settlement. Spawning stock is not significant.
	(Caputi, Chubb et al.).	1993	Whitebait *Hyperplphus vittatus*	Significant positive correlation (*r*=0.86) between whitebait catch and strength of Leeuwin Current off Western Australia.
	(Fletcher, Tregonning *et al.*)	1994	Pilchards *Sardinops sagax neopilchardus*	Geographical discontinuities of the early life stages of the pilchard in response to changes in the Leeuwin Current define later population structures.
	(Joll and Caputi)	1995	Saucer scallop *Amusium balloti*	Strength of recruitment significantly correlated (*r*=-0.86) with the strength of the Leeuwin current during the spawning season.
	(Caputi, Fletcher et al.).	1996	Pilchards *Sardinops sagax neopilchardus*	Significant positive correlation between strength of 2 year old recruits and the Leeuwin current in June/July (*r*=0.87).
	(Caputi, Penn et al.).	1998	Shark Bay Scallops	Inverse relationship (*r*=-0.79) between sea level (and therefore ENSO) and subsequent recruitment of the scallop.
	(Caputi, Chubb et al.).	2001	Western Rock Lobster *Panulirus cygnus*	February–April sea level and SST associated with the Leeuwin Current and ENSO affects lobster settlement, however relationships lobster temporally inconsistent with variable responses in some years depending on SSTs.
	(Caputi, Chubb *et al.*)	2003	Western Rock Lobster *Panulirus cygnus*	The south-flowing Leeuwin Current significantly influences the level and spatial distribution of the lobster settlement along the coast.

Site	Author	Year	Species	Key Findings
NT	(Griffin)	1985	Barramundi *Lates calcarifer*	Variations in wet season rainfall and resulting area of flooded, shallow, grassy floodplain nursery habitats, impact on survival of 8 – 200 mm barramundi.
	(Griffin)	1986	Barramundi *Lates calcarifer*	Correlation between juvenile abundance and early wet season rainfall (*r*=0.81), CPUE and previous wet season rainfall also significant (*r*=0.69).
	(Love)	1987	Banana prawn *Penaeus merguiensis*	Significant positive correlation between total prawn catch/CPUE and Troup's SOI for preceding November (*r*=0.83 / *r*=0.80 respectively)
SA	(Lenanton, Joll *et al.*)	1991	Australian Salmon *Arripis truttaceus*	Significant positive correlation between 0+ recruitment and strength of the Leeuwin current and negative relationship between current strength and catchability off south-west beaches.
			Australian Herring *Arripis geogianus*	Significant positive correlation between 0+ recruitment and strength of the Leeuwin current.
	(Caputi, Fletcher et al.).	1996	Australian Herring *Arripis geogianus*	Significant positive correlation between 0+ recruitment and strength of the Leeuwin current.
VIC	(Humphries, Lake *et al.*)	2001	Native freshwater fish	River regulation has altered the Campaspe River macroinvertebrate communities creating unfavourable conditions for recruitment of young fish through interactions between hydrology, habitat and food availability.
	(Young, Bradford *et al.*)	2001	Yellowfin Tuna *Thunnus albacares*	Warm eddy areas increase the levels of chlorophyll a, zooplankton and micronekton and correlate with CPUE.
	(Jenkins)	2005	King George Whiting *Sillaginodes punctata*	A significant positive correlation between the strength of ZWW in the region and catch 3 to 5 years later (*r*=0.43; *r*=0.44) in Port Phillip Bay. Significant positive correlation between ENSO and catch at 0 lag (*r*=0.31).
TAS	(Harris, Davies *et al.*)	1988	Brown Trout *Salmo trutta fario*	Significant correlation between mean maximum air temperature and numbers of 3 year old brown trout (*r*=0.53).
			Lobster	Significant relationship between TAS, NSW and NZ lobster catch and ZWW, Darwin, Hobart and Macquarie Island atmospheric air pressure.
	(Harris, Griffiths *et al.*)	1992	Jack Mackerel *Trachurus declivis*	Changes in geographical distribution in response to SSTs, ENSO and ZWW.
	(Thresher)	1994	Gemfish *Rexea solandri*	Peaks of gemfish recruitment match periods of strong ZWW. No strong or consistent relationship found between gemfish recruitment and ENSO.

REFERENCES:

Caputi N, Brown RS (1993) The effect of environment on puerulus settlement of the western rock lobster (*Panulirus cygnus*) in Western Australia. *Fisheries Oceanography* **2**, 1-10.

Caputi N, Chubb CF, Brown RS (1993) Relationships between spawning stock, envirnonment, recruitment and fishing effort for the western rock lobster, *Panulirus cygnus*, fishery in Western Australia. In 'Fourth International Workshop on Lobster Biology and Management' pp. 213-226

Caputi N, Chubb CF, Melville-Smith R, Pearce A, Griffin D (2003) Review of relationships between life history stages of the western rock lobster, *Panulirus cygnus*, in Western Australia. *Fisheries Research* **65**, 47-61.

Caputi N, Chubb CF, Pearce A (2001) Environmental effects on recruitment of the western rock lobster, *Panulirus cygnus*. *Marine and Freshwater Research* **52**, 1167-1174.

Caputi N, Fletcher WJ, Pearce A, Chubb CF (1996) Effect of the Leeuwin Current on the recruitment of fish and invertebrates along the Western Australian coast. *Marine Freshwater Research* **47**, 147-155.

Caputi N, Penn JW, Joll LM, Chubb CF (1998) Stock-recruitment-environment relationships for invertebrate species of Western Australia. In 'North Pacific Symposium on Invertebrate Stock Assessment and Management'. (Eds GS Jamieson and A Campbell) pp. 247-255. (Canadian Special Publication of Fisheries Aquatic Science).

Catchpole A, Auliciems A (1999) Southern oscillation and the northern australian prawn catch. *International Journal of Biometeorology* **43**, 110-112.

Davis TLO (1985) Seasonal changes in gonad maturity, and abundance of larval and early juveniles of barramundi, *Lates calcarifer* (Bloch), in Van Diemen Gulf and the Gulf of Carpentaria. *Australian Journal of Marine and Freshwater Research* **36**, 177-190.

Dredge MCL (1985) Importance of estuarine overwintering in the life cycle of the banana prawn, *Penaeus merguiensis*. In 'Second Australian National Prawn Seminar'. Brisbane, Australia pp. 115-124. (CSIRO).

Dunstan DJ (1959) 'The barramundi *Lates calcarifer* (Bloch) in Queensland waters.' CSIRO, Melbourne.

Fletcher WJ, Tregonning RJ, Sant GJ (1994) Interseasonal variation in the transport of pilchard eggs and larvae off southern Western Australia. *Marine Ecology Progress Series* **111**, 209-224.

Glaister JP (1978) The impact of river discharge on distribution and production of the school prawn *Metapenaeus macleayi* (Haswell) (Crustacea: Penaediae) in the Clarence River Region, Northern New South Wales. *Australian Journal of Marine and Freshwater Research* **29**, 311-323.

Griffin RK (1985) The importance of mangrove / coastal wetland to three commercial fisheries in the Northern Territory particularly for barramundi (*Lates calcarifer*). In 'Coasts and tidal wetlands of the Australian monsoon region'. (Eds KN Bardsley, JDS Davie and CD Woodroffe). (Australian National University: Darwin)

Griffin RK (1986) Barramundi (*Lates calcarifer)* research in Northern Territory, Australia. In 'Management of wild and cultured Sea Bass/Barramundi *(Lates calcarifer)*'. Darwin, Australia. (Eds JW Copland and DL Grey) pp. 87-91. (Australian Centre for International Agricultural Research).

Harris GP, Davies P, Nunuz M, Meyers G (1988) Interannual variability in climate and fisheries in Tasmania. *Nature* **333**, 754-757.

Harris GP, Griffiths FB, Clementson LA (1992) Climate and the fisheries off Tasmania - Interactions of physics, food chains and fish. *South African Journal of Marine Science* **12**, 585-597.

Humphries P, Lake S, Growns S (2001) 'Effect of flow manipulation on the biota of a lowland river.' Land and Water Resources Research and Development Corporation.

Isdale PJ (1984) Fluorescent bands in massive corals record centuries of coastal rainfall. *Nature* **310**, 578-579.

Isdale PJ, Stewart BJ, Tickle KS, Lough JM (1988) Palaeohydrological variation in a tropical river catchment: a reconstruction using fluorescent bands in corals of the Great Barrier Reef, Australia. *The Holocene* **8**, 1-8.

Jenkins GP (2005) Influence of climate on the fishery recruitment of a temperate, seagrass-associated fish, the King George whiting *Sillaginodes punctata*. *Marine Ecology Progress Series* **288**, 263-271.

Joll LM, Caputi N (1995) Environmental influences on recruitment in the saucer scallop (*Amusium balloti*) fishery of Shark Bay, Western Australia. In 'Shellfish life histories and shellfishery models'. Moncton, New Brunswick, Denmark. (Eds DE Aiken, SL Waddy and GY Conan) pp. 47-53. (ICES Copenhagen (Denmark)).

Lenanton RCJ, Joll LM, Penn JW, Jones K (1991) The influence of the Leeuwin Current on coastal fisheries of Western Australia. *Journal of the Royal Society of Western Australia* **74**, 101-114.

Limpus C, Nicholls N (2000) ENSO regulation of Indo-Pacific green turtle populations. In 'Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems'. (Eds GL Hammer, N Nicholls and C Mitchell) pp. 399-408. (Kluwer Academic Publishers)

Loneragan NR, Potter IC, Lenanton RCJ, Caputi N (1987) Influence of environmental variables on the fish fauna of the deeper waters of a large Australian estuary. *Marine Biology* **94**, 631-641.

Lough JM, Barnes DJ (1990) Possible relationships between environmental variables and skeletal density in a coral colony from the central Great Barrier Reef. *Journal of Experimental Marine Biology and Ecology* **134**, 221-241.

Love G (1987) Banana prawns and the Southern Oscillation Index. *Australian Meteorological Magazine* **35**, 47-49.

Meager JJ, Vance DJ, Loneragan NR, Williamson I (2003) Seasonal variation and environmental influences on juvenile banana prawn (*Penaeus merguiensis*) abundance in a subtropical estuary (Logan River) of eastern Australia. *Estuarine, Coastal and Shelf Science* **57**, 569-576.

Meynecke JO, Lee SY, Duke N, Warnken J (2006) Effect of rainfall as a component of climate change on estuarine fish production in Queensland, Australia. *Estuarine, Coastal and Shelf Science* **69**, 491-504.

Milicich MJ (1994) Dynamic coupling of reef fish replenishment and oceanographic processes. *Marine Ecology Progress Series* **110**, 135-144.

Pearce AF (1988) ENSO events, the Leeuwin Current, and larval recruitment of the western rock lobster. *Journal du Conseil International pour l'Éxploration de la Mer* **45**, 13-21.

Penn JW, Caputi N (1986) Spawning stock-recruitment relationships and environmental influences on the Tiger Prawn (*Penaeus esculentus*) fishery in Exmouth Gulf, Western Australia. *Australian Journal of Marine and Freshwater Research* **37**, 491-505.

Platten JR (1996) 'The influence of river freshwater discharge on fishery catch rates in Queensland waters.' Department of Natural Resources, Rockhampton.

Platten JR (1999) 'Historical trends in recreational fishing catches.' Gladstone Area Waterboard, Rockhampton.

Robins JB, Halliday IA, Staunton-Smith J, Mayer DG, Sellin MJ (2005) Freshwater flow requirements of estuarine fisheries in tropical Australia: a review of the state of knowledge and application of a suggested approach. *Marine and Freshwater Research* **56**, 343-360.

Robins JB, Mayer DG, Staunton-Smith J, Halliday IA, Sawynok B, Sellin MJ (2006) Variable growth rates of a tropical estuarine fish species (barramundi, *Lates calcarifer* Bloch) under different freshwater flow conditions. *Journal of Fish Biology* **69**, 379-391.

Ruello NV (1973) The influence of rainfall on the distribution and abundance of the school prawn *Metapenaeus macleayi* in the Hunter River region (Australia). *Marine Biology* **23**, 221-228.

Sawynok B (1998) 'Fitzroy river effects of freshwater flows on fish.' InfoFish Services, Rockhampton.

Sheaves M (1998) Spatial patterns in estuarine fish faunas in tropical Queensland: a reflection of interaction between long-term physical and biological processes? *Marine and Freshwater Research* **49**, 31-40.

Staples DJ (1985) Modelling the recruitment processes of the banana prawn, *Penaeus merguiensis*, in the southeastern Gulf of Carpentaria, Australia. In 'Second Australian National Prawn Seminar'. Cleveland, Australia. (Eds PC Rothlisberg, BJ Hill and DJ Staples) pp. 175-184. (NPS2).

Staples DJ, Vance DJ (1986) Emigration of juvenile banana prawns *Penaeus merguiensis* from a mangrove estuary and recruitment to offshore areas in the wet-dry tropics of the Gulf of Carpentaria, Australia. *Marine Ecology Progress Series* **27**, 239-252.

Staunton-Smith J, Robins JB, Sellin MJ, Halliday IA, Mayer DG (2004) Does the timing of freshwater flowing into a dry tropical estuary affect year-class strength of barramundi (*Lates calcarifer*)? *Marine and Freshwater Research* **55**, 787-797.

Stephenson W, Williams MJ (1981) Analysis of south Queensland prawn catches landed at Queensland fish board depots. *Proceedings of the Royal Society of Queensland* **92**, 57-74.

Thresher R (1994) Climate cycles may help explain fish recruitment in south-east Australia. In 'Australian Fisheries'.

Vance DJ, Bishop J, Dichmont CM, Hall N, McInnes K, Taylor BR (2003) 'Management of common banana prawn stocks of the Gulf of Carpentaria: separating the effects of fishing from those of the environment.' CSIRO Marine Research, Project No. 98/0716, Cleveland.

Vance DJ, Haywood MDE, Heales DS, Kenyon RA, Loneragan NR (1998) Seasonal and annual variation in abundance of postlarval and juvenile banana prawns *Penaeus merguiensis* and environmental variation in two estuaries in tropical northeastern Australia: a six year study. *Marine Ecology Progess Series* **163**, 21-36.

Vance DJ, Haywood MDE, Heales DS, Staples DJ (1996) Seasonal and annual variation in abundance of postlarval and juvenile grooved tiger prawns *Penaeus semisulcatus* and environmental variation in two estuaries in the Embley River, Australia: a six year study. *Marine Ecology Progess Series* **135**, 43-55.

Vance DJ, Staples DJ, Kerr JD (1985) Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus merguiensis*) in the Gulf of Carpentaria, Australia. *Journal du Conseil International pour L'Exploration de la Mer* **42**, 83-97.

Young JW, Bradford RW, Lamb TD, Clementson LA, Kloser R, Galea H (2001) Yellowfin tuna (*Thunnus albacares*) aggregations along the shelf break off south-eastern Australia: links between inshore and offshore processes. *Marine and Freshwater Research* **52**, 463-474.