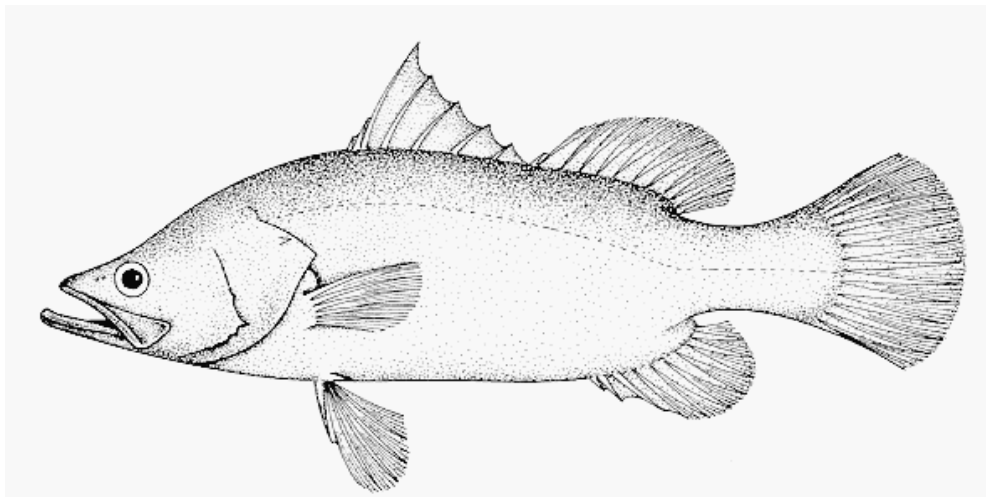


**AN EXAMINATION OF THE IMPACTS OF CLIMATE VARIABILITY AND
CLIMATE CHANGE ON THE WILD BARRAMUNDI (*Lates calcarifer*): A
TROPICAL ESTUARINE FISHERY OF NORTH-EASTERN QUEENSLAND,
AUSTRALIA.**



Thesis submitted by
Jacqueline Marie BALSTON BSc QLD
in April 2007

for the degree of Doctor of Philosophy
in the School of Earth and Environmental Sciences
James Cook University

ELECTRONIC COPY

I, the undersigned, the author of this work, declare that the electronic copy of this thesis provided to the James Cook University Library, is an accurate copy of the print thesis submitted, within the limits of the technology available.

Signature

Date

STATEMENT OF ACCESS

I, the undersigned, the author of this thesis understand that James Cook University will make it available for use within the university library and, via the Australian Digital Theses network, for use elsewhere.

I understand that, as an unpublished work, a thesis has significant protection under the Copyright Act and beyond this I do not wish to place any restrictions on access to this thesis.

Users of theses are advised that the policy for preparation and acceptance of theses does not guarantee that they are entirely free of inappropriate analysis or conclusions. Users may direct enquiries regarding particular theses to the relevant school head.

Signature

Date

STATEMENT OF SOURCES

I declare that this thesis is my own, original work carried out under the supervision of James Cook University School of Earth and Environmental Sciences. No part of this work has been submitted in any form for another degree or diploma at any other university or institution of tertiary education. Any work that is not my own has been acknowledged in the text by appropriate references.

Signature

Date

STATEMENT ON THE CONTRIBUTION BY OTHERS

Fees: Nil

Stipend support: Queensland Department of Primary Industries and Fisheries

Supervision: Neil Gribble, Roger Stone and Steve Turton.

Other collaborations: Allyson Williams, co-author of a reviewed paper presented at the 2005 MODSIM conference in Melbourne.

Statistical support: Sarah Lennox, Bob Mayer, David Mayer and Angela Reid.

Editorial assistance: Doug Abrecht, Kate Balston, Rosemary Dunn, Adella Edwards, Brian Hansen, Elaine Harding and Neil White.

Research assistance: Yahya Abawai, Graham Farquhar, Rod Garrett, Ian Halliday, Elaine Harding, Mark Howden, Holger Meinke, Jonathan Nott, Andreas Potgeitger, Julie Robins, Mike Roderick, Jonathan Staunton-Smith, Penny Whetton and Allyson Williams.

Any other assistance: Nil.

Project funding: CRC for Coastal Zone Estuary and Waterways Management (\$60,000), Queensland Department of Primary Industries and Fisheries (\$20,000).

Use of infrastructure external to JCU: The Queensland Department of Primary Industries and Fisheries offices.

Use of infrastructure external to organisational unit within JCU: Nil.

ACKNOWLEDGEMENTS

No thesis is accomplished alone. I would like to thank my supervisors Drs Steve Turton, Neil Gribble and Roger Stone for their enthusiasm, questioning, advice and support throughout the term of my PhD. Gratitude and thanks also to: Sarah Lennox, Bob Mayer, David Mayer and Angela Reid for their statistical advise and input; Rod Garrett, Dr Julie Robbins, Ian Halliday and Jonathon Staunton-Smith for sharing their knowledge on barramundi and fisheries production systems of which I had none at the beginning of this project; Drs Allyson Williams, Holger Meinke, Yahya Abawi, Andreas Potgeitger, Penny Whetton, Mike Roderick, Graham Farquhar, Jonathan Nott and Mark Howden for their provision of climate data, technical advice and expertise in climatology and climate change; Drs Doug Abrecht, Elaine Harding, Neil White and Rosemary Dunn for their labours in reading numerous drafts. Sincere thanks also to all my dear friends and family who have listened to endless single topic telephone conversations and provided emotional and at times technical support. To Brian for his love and support, and my Mum and Dad for many years of the same and for providing me with all the opportunities in life without which this quodlibet would not have been possible!

PUBLICATIONS PRODUCED AS A RESULT OF THIS STUDY

Peer reviewed journals conference proceedings and reports:

Balston, J. M. (In press). Impacts of climate variability and climate change on the Wet Tropics of north-eastern Australia. In: Living in a Dynamic Tropical Landscape. (Eds: N. Stork and S. M. Turton). London., Blackwells.

Balston, J.M. and Williams, A.J. (2005). Modelling impacts of climate variability on the commercial barramundi (*Lates calcarifer*) fishery of north-eastern Queensland, MODSIM 05 International Congress on Modelling and Simulation, 12-15 December 2005, Melbourne, Australia.

Balston, J.M., and Williams, A.A.J. (2006). Aquaculture and Fisheries In: Vulnerability to Climate Change of Australia's Coastal Zone: Analysis of gaps in methods, data and system thresholds. Part I: Executive and Technical Summaries (Eds: Voice, M., Harvey, N. and Walsh, K.). Report to the Australian Greenhouse Office, Canberra, Australia.

Balston, J. (2007). Climate impacts on the barramundi and banana prawns fisheries of the Queensland tropical east coast. In: Environmental flows for sub-tropical estuaries: understanding the freshwater needs of estuaries for sustainable fisheries production and assessing the impacts of water regulation (Eds: Halliday, I. and Robins, J.). Final Report for the Fisheries Research and Development Corporation Project Number 2001/022 and the Coastal Zone Cooperative Research Centre Projects FH3/AF. Queensland Department of Primary Industries and Fisheries, Brisbane, Queensland. 62-77.

Stork, N.E., Balston, J., Farquhar, G.D., Franks, P.J., Holtum, J.A.M., Liddell, J.M. (2007). "Tropical rainforest canopies and climate change". *Austral Ecology* 32:105-112.

Other:

Balston, J.M. (2006). Modelling impacts of climate variability on the commercial barramundi fishery of north-eastern Queensland, GulfMac Annual General Meeting, 12 October 2006, Cairns, Australia.

Balston, J.M. (2005). Climate Impacts on the barramundi and banana prawn fisheries of Princess Charlotte Bay, Annual Conference of the CRC for Coastal Zone Estuary and Waterways Management, 14 September 2005, Coolangatta, Australia.

Balston, J.M. (2004). Effects of seasonal climate variability on barramundi (*Lates calcarifer*) fisheries productivity in the Great Barrier Reef World Heritage Area, Australian Society Fish Biology Conference, 19-24 September 2004, Adelaide, Australia.

Balston, J.M. (2001). Effects of seasonal climate variability on barramundi fishery productivity in the Great Barrier Reef World Heritage Area. 14th Australia and New Zealand Climate Forum. Darwin 18-21 September 2001.

Journal articles in preparation for submission by 30th June 2007:

Balston, J.M. (in prep) “An examination of the impacts of short-term climate effects on the wild barramundi fishery of Princess Charlotte Bay and implications for management”.

Balston, J.M. (in prep) “An examination of the impacts of long-term climate effects on the catch of wild barramundi fishery in north-east Queensland”.

Balston, J.M. (in prep) “The impact of extreme and threshold climate events on the catch of wild barramundi fishery in Princess Charlotte Bay, north-east Australia”.

Balston, J.M. (in prep) “The impacts of climate change on the wild barramundi fishery of Princess Charlotte Bay, north-east Australia”.

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

TABLE OF CONTENTS

STATEMENT OF ACCESS	II
STATEMENT OF SOURCES	III
STATEMENT ON THE CONTRIBUTION BY OTHERS	IV
ACKNOWLEDGEMENTS	V
PUBLICATIONS PRODUCED AS A RESULT OF THIS STUDY	VI
PEER REVIEWED JOURNALS CONFERENCE PROCEEDINGS AND REPORTS:	VI
OTHER:	VII
JOURNAL ARTICLES IN PREPARATION FOR SUBMISSION BY 30TH JUNE 2007:	VII
ABSTRACT	VIII
SCOPE	VIII
METHODS	VIII
RESULTS	IX
CONCLUSIONS	X
ACRONYMS	XI
GLOSSARY	XII
TABLE OF CONTENTS	XIII
LIST OF TABLES	XIX
LIST OF FIGURES	XXII
LIST OF PLATES	XXVI
CHAPTER 1: INTRODUCTION	1
1.1 PREAMBLE	1
1.2 RATIONALE FOR THIS RESEARCH	2
1.3 RESEARCH AIMS	3
1.4 THESIS STRUCTURE AND OUTLINE	4
CHAPTER 2: A REVIEW OF THE EFFECTS OF CLIMATE VARIABILITY ON WILD FISHERIES	6
2.1 INTRODUCTION	6
2.2 OVERSEAS RESEARCH	9
<i>SSTs and long-term climate variability and ENSO</i>	9
<i>Rainfall and freshwater flows</i>	11
<i>Other climate variables</i>	12
2.3 AUSTRALIAN RESEARCH	13
<i>SSTs and ENSO</i>	13
<i>Rainfall and freshwater flows</i>	16
<i>Wind</i>	16

<i>Other climate variables</i>	17
2.4 THE BARRAMUNDI AND IMPACTS FROM CLIMATE	18
<i>The barramundi</i>	18
<i>Species distribution</i>	19
<i>Habitat</i>	20
<i>Biology and life cycle</i>	21
<i>Feeding habits</i>	24
<i>Impacts of climate on the barramundi</i>	25
Rainfall and freshwater flow.....	25
Water temperature.....	27
2.5 SUMMARY	28
CHAPTER 3: METHODOLOGY	31
3.1 INTRODUCTION	31
3.2 METHODOLOGY	31
<i>Development of a barramundi life cycle model</i>	32
<i>Development of a hypothesis</i>	34
<i>Selection of suitable study area and barramundi fishery</i>	35
<i>Collation of fisheries catch and climate data</i>	37
<i>Analyses</i>	39
3.3 SUMMARY	40
CHAPTER 4: SHORT-TERM CLIMATE EFFECTS: PRINCESS CHARLOTTE BAY	41
4.1 INTRODUCTION	41
4.2 STUDY AREA	41
<i>Topography</i>	42
<i>River systems</i>	43
<i>Land use</i>	43
<i>Climate</i>	43
<i>Estuaries and coastal zone</i>	44
<i>Barramundi habitat</i>	44
4.3 DATA	45
<i>Commercial fisheries logbook (CFISH) data</i>	45
<i>Climate data</i>	47
Rainfall.....	47
Freshwater flow	48
Terrestrial air temperature and evaporation.....	51
Sea surface temperatures (SSTs)	52
Indices of the Southern Oscillation (SOI).....	52
Indices of the Madden Julian Oscillation (MJO).....	53

Data collation	54
4.4 METHODS	57
<i>Hypotheses</i>	57
4.5 RESULTS	59
<i>Exploratory analysis</i>	59
<i>Correlation matrix</i>	60
<i>Lag analysis</i>	62
4.6 DISCUSSION	63
4.7 CONCLUSION	70
CHAPTER 5: COMPARATIVE ANALYSIS: FITZROY RIVER AREA.....	72
5.1 INTRODUCTION	72
5.2 STUDY AREA	72
<i>Topography</i>	72
<i>River systems</i>	72
<i>Land use</i>	73
<i>Estuaries and coastal zone</i>	74
<i>Climate</i>	74
<i>Barramundi habitat</i>	75
5.3 DATA	75
<i>Commercial fisheries logbook (CFISH) data</i>	75
<i>Climate Data</i>	77
Rainfall.....	77
Freshwater flow	77
Terrestrial air temperature and evaporation.....	77
Sea surface temperature (SST)	77
Indices of the Southern Oscillation (SOI).....	78
Indices of the Madden Julian Oscillation (MJO).....	78
5.4 METHODS	78
<i>Hypotheses</i>	78
5.5 RESULTS	81
<i>Exploratory analysis</i>	81
<i>Correlation matrix</i>	82
<i>Lag analysis</i>	84
5.6 DISCUSSION	85
5.7 CONCLUSION.....	90
CHAPTER 6: EXTREME AND THRESHOLD CLIMATE EVENTS	92
6.1 INTRODUCTION	92
6.2 BACKGROUND	92
6.3 DATA	94
6.4 METHODOLOGY	95
<i>Hypotheses</i>	97

6.5	RESULTS	97
	<i>Quantitative analysis</i>	97
	<i>Qualitative analysis</i>	100
6.6	DISCUSSION	106
6.7	CONCLUSION.....	109
CHAPTER 7: LONG-TERM CLIMATE EFFECTS: NORTH-EAST QUEENSLAND		111
7.1	INTRODUCTION	111
7.2	STUDY AREA	112
	<i>Topography</i>	113
	<i>River systems</i>	113
	<i>Land use</i>	114
	<i>Climate</i>	114
7.3	DATA	116
	<i>Fisheries data</i>	116
	<i>Climate data</i>	119
	The Interdecadal Pacific Oscillation (IPO).....	119
	The Quasi-Biennial Oscillation (QBO)	119
	The Southern Hemisphere Annular Mode (SAM).....	120
	Latitude of the Sub-tropical Ridge (LSTR)	121
7.4	METHODS	122
	<i>Hypotheses</i>	124
7.5	RESULTS	125
	<i>Exploratory analysis</i>	125
	<i>Correlation matrix</i>	127
	<i>Lag Analysis</i>	128
	<i>Time series graphs</i>	128
4.6	DISCUSSION	128
7.7	CONCLUSION.....	133
CHAPTER 8: PREDICTIVE MODEL DEVELOPMENT.....		134
8.1	INTRODUCTION	134
8.2	EXISTING BARRAMUNDI FISHERIES MODELS	134
8.3	DATA	137
8.4	METHODS	137
	<i>Systems dynamic model</i>	137
	<i>Statistical models</i>	138
8.5	RESULTS	140
8.6	DISCUSSION	145
8.7	CONCLUSION.....	147
CHAPTER 9: EFFECTS OF CLIMATE CHANGE: PRINCESS CHARLOTTE BAY		148

9.1	INTRODUCTION	148
9.2	BACKGROUND	148
	<i>Climate Change – Existing Trends</i>	149
	Temperature	149
	Rainfall.....	149
	Evaporation.....	151
	Sea levels	152
	Tropical cyclones.....	152
	<i>Climate Change – Future Trends</i>	152
	Temperature	153
	Rainfall.....	153
	Evaporation.....	156
	Sea levels	156
	Tropical cyclones.....	157
9.3	CLIMATE CHANGE AND PRINCESS CHARLOTTE BAY	157
	<i>Temperature</i>	157
	<i>Rainfall</i>	158
	<i>Evaporation</i>	159
	<i>Wind</i>	160
	<i>Tropical cyclones</i>	161
9.4	IMPACT OF CLIMATE CHANGE ON FISHERIES	161
9.5	DATA	163
9.6	METHODOLOGY	163
	<i>Hypotheses</i>	166
9.7	RESULTS	166
9.8	DISCUSSION	173
9.9	CONCLUSION.....	179
CHAPTER 10: SYNTHESIS, RECOMMENDATIONS AND CONCLUSIONS		180
10.1	INTRODUCTION	180
10.2	KEY RESULTS FROM THIS RESEARCH.....	180
	<i>The climate of north-east Queensland</i>	180
	<i>Short-term climate effects: Princess Charlotte Bay</i>	182
	<i>Comparative analysis: Fitzroy River area</i>	182
	<i>Extreme and threshold climate events</i>	183
	<i>Long term climate effects: North-east Queensland</i>	184
	<i>Predictive model development</i>	185
	<i>Effects of climate change: Princess Charlotte Bay</i>	186
	<i>Key findings</i>	186
10.3	PAST AND PRESENT MANAGEMENT OF THE BARRAMUNDI FISHERY	187

10.4	IMPLICATIONS OF THIS RESEARCH FOR FUTURE MANAGEMENT OF THE BARRAMUNDI FISHERY	189
	<i>Preservation of wetlands</i>	189
	<i>Preservation of environmental flows</i>	189
	<i>Regulation of fishing pressure</i>	190
	<i>Consideration of climate change</i>	190
10.5	RECOMMENDATIONS FOR FUTURE RESEARCH	191
	REFERENCES	193
	APPENDICES (ON ATTACHED CD)	229
	APPENDIX 1: SUMMARY OF REVIEWED STUDIES OVERSEAS	229
	APPENDIX 2: SUMMARY OF REVIEWED STUDIES AUSTRALIA	229
	APPENDIX 3: SCATTER PLOTS OF BARRAMUNDI CATCH ADJUSTED FOR EFFORT VERSUS SHORT-TERM CLIMATE VARIABLES – PRINCESS CHARLOTTE BAY AREA	229
	APPENDIX 4: SCATTER PLOTS OF BARRAMUNDI CATCH ADJUSTED FOR EFFORT VERSUS SHORT-TERM CLIMATE VARIABLES – FITZROY RIVER AREA	229
	APPENDIX 5: SCATTER PLOTS OF BARRAMUNDI CATCH ADJUSTED FOR EFFORT VERSUS LONG-TERM CLIMATE VARIABLES – NORTH EAST QUEENSLAND	229
	APPENDIX 6: PRINCESS CHARLOTTE BAY AREA ANALYSES – DATA, ANALYSES AND RESULTS	229
	APPENDIX 7: FITZROY RIVER AREA ANALYSES – DATA, ANALYSES AND RESULTS..	229
	APPENDIX 8: THRESHOLDS AND EXTREME EVENTS ANALYSES – DATA, ANALYSES AND RESULTS	229
	APPENDIX 9: LONG-TERM ANALYSES – DATA, ANALYSES AND RESULTS	229
	APPENDIX 10: PREDICTIVE MODEL ANALYSES – DATA, ANALYSES AND RESULTS .	229
	APPENDIX 11: CLIMATE CHANGE ANALYSES – DATA, ANALYSES AND RESULTS....	229

LIST OF TABLES

Table 2.1	River classification and barramundi habitat	22
Table 2.2	A summary of previous research linking climate variables with barramundi catch and recruitment in Australia.	30
Table 3.1	Example general hypothesis linking climate variability and commercial barramundi catch for north-east Queensland.	35
Table 4.1	Selected stream gauges in the Princess Charlotte Bay study area.	48
Table 4.2	Gamma correlations (r) between Princess Charlotte Bay river flows and total basin flow into the Bay (1971 – 1987)..	50
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.	51
Table 4.4	Data used in the analyses of short-term climate effects on the barramundi fishery of Princess Charlotte Bay.	56
Table 4.5	Hypothesis linking climate variability and commercial barramundi catch for north-east Queensland	59
Table 4.6	Pearson coefficients of correlation (r) of climate parameters used in the Princess Charlotte Bay analyses.	61
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).	62
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).....	63
Table 4.9	Summary of findings from the correlation analyses between Princess Charlotte Bay barramundi catch and short-term climate parameters	70
Table 5.1	A comparison of the Princess Charlotte Bay and Fitzroy River areas.....	75
Table 5.2	Data used in the analyses of short-term climate effects on the Fitzroy River area barramundi fishery	80
Table 5.3	Hypothesis linking climate variability and commercial barramundi catch for the Fitzroy River area.	81

Table 5.4	Pearson coefficient of correlation (<i>r</i>) matrix of climate variables and indices for the Fitzroy River area.....	83
Table 5.5	Pearson coefficient of correlation (<i>r</i>) between Fitzroy River area barramundi CFISH catch adjusted for effort (1989/90 – 2002/03) and climate variables (zero – five year lag).....	84
Table 5.6	Pearson coefficient of correlation (<i>r</i>) between Fitzroy River area barramundi CFISH catch adjusted for effort (1989/90 – 2002/03) and climate indices (zero – five year lag).....	85
Table 5.7	Summary of findings from the correlation analyses between short-term climate parameters and Fitzroy River area barramundi catch	90
Table 6.1	Hypothesis linking extreme and threshold climate events and commercial barramundi catch for north-east Queensland.....	98
Table 6.2	Droughts affecting the Princess Charlotte Bay area (1970 – 2006) for 120 years of rainfall data at Lakefield.....	103
Table 6.3	Tropical cyclones affecting the Princess Charlotte Bay area (1970 – 2006)..	107
Table 7.1	Fish Board data for north-east Queensland (Queensland Fish Board 1937 – 1981).	117
Table 7.2	Fisheries and climate data used in the identification of effects from long-term climate cycles on the commercial barramundi fishery of north-east Australia... ..	123
Table 7.3	Hypothesis linking long-term climate cycles and commercial barramundi catch as recorded by north-east Queensland Fish Board depots.....	125
Table 7.4	Pearson correlation coefficient (<i>r</i>) matrix of Fish Board regional barramundi landings across north-east Queensland.....	127
Table 7.5	Pearson correlation coefficient (<i>r</i>) between long-term climate indices and Fish Board barramundi landings for north-east Queensland (zero – five year lag).....	128
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..	133
Table 8.1	Variables included in the statistical modelling of Princess Charlotte Bay barramundi catch.....	138
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).....	142

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).....	144
Table 9.1	Rainfall scenarios generated to determine impacts of climate change on the barramundi fishery of Princess Charlotte Bay.....	169
Table 9.2	Evaporation scenarios generated to determine impacts of climate change on the barramundi fishery of Princess Charlotte Bay.....	169
Table 9.3	Each of the synthetic climate change scenarios entered into the Princess Charlotte Bay barramundi Predictive Model I.....	170
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.	172

LIST OF FIGURES

Figure 1.1	Flow chart outlining the structure of the thesis and chapter content.	5
Figure 2.1	The two extremes of ENSO.....	9
Figure 2.2	Location of studies linking climate and fisheries in Australia.....	144
Figure 2.3	Map of Queensland, Australia showing the distribution of barramundi genetic stock.	20
Figure 2.4	Diagram of the barramundi life cycle showing the significant stages and key habitats	22
Figure 3.1	Conceptual process model developed for determination of the impacts of climate on the barramundi fishery of north-east Queensland.	32
Figure 3.2	Life cycle model of the barramundi including known influences from climate at each stage in the development of the fish.	33
Figure 3.3	Conceptual model of the impact of sea surface temperatures (SST) and evaporation (E) on early barramundi life cycle stages.	34
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 region near Rockhampton.	36
Figure 3.5	Sources of catch and effort data for the Queensland east coast barramundi fishery.	38
Figure 4.1	The Princess Charlotte Bay study area	42
Figure 4.2	CFISH grid squares for the Princess Charlotte Bay study area.	46
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).	47
Figure 4.4	Princess Charlotte Bay river flow from January 1971 to February 1987... ..	49
Figure 4.5	Observed vs modelled monthly basin flow for Princess Charlotte Bay (1971 – 1987).	52
Figure 4.6	Annual average rainfall for the Musgrave and Laura recording stations in the Princess Charlotte Bay study area (Australian Rainman).	60
Figure 5.1	Fitzroy River study area.....	73
Figure 5.2	CFISH grid squares for the Fitzroy River study area	76

Figure 5.3 Annual financial year CFISH barramundi catch (bars) and effort (line) for the Fitzroy River area (1989/90 – 2002/03).....	76
Figure 5.4 Annual rainfall at Yaamba in the Fitzroy River area (1900 – 2004)	82
Figure 6.1 Proposed methodology for identifying non-linear climate driven responses in a fishery	96
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.	99
Figure 6.3 Scatter plot of annual evaporation versus barramundi catch adjusted for effort (CAE) two years later	100
Figure 6.4 Observed (1971 – 1987) and modelled (1988 – 2004) total monthly basin flow for Princess Charlotte Bay.....	101
Figure 6.5 Observed and modelled seasonal Princess Charlotte Bay basin flow 1971 – 2006 (bars) and Lakefield seasonal rainfall 1971 – 2006 (line)	102
Figure 7.1 North-east Queensland study area.	112
Figure 7.2 Average annual rainfall for north-east Queensland 1961 – 1990	115
Figure 7.3 Average (a) maximum and (b) minimum air temperature for north-east Queensland 1961 – 1990.....	115
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.....	118
Figure 7.5 Total annual financial year (1 July – 30 June) Fish Board barramundi landings for north-east Queensland (1945/46 – 1980/81).	118
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)..	126
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).....	127
Figure 7.8 Fish Board barramundi landings for north-east Queensland (1953/54 – 1980/81) versus the <i>L</i> -index (three years previous).....	129
Figure 8.1 A conceptual systems dynamic model of climate influences on the Princess Charlotte Bay barramundi fishery.....	139
Figure 8.2 Predicted values of Princess Charlotte Bay barramundi catch adjusted for effort (CAE) from Predictive Model I versus observed.	142

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).	143
Figure 8.4 Predicted values of Princess Charlotte Bay barramundi catch adjusted for effort (CAE) from Predictive Model II versus observed.	144
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).	145
Figure 9.1 Changes in Queensland maximum and minimum temperature and diurnal temperature range.	150
Figure 9.2 Annual rainfall for Cairns (1901 – 2001).	151
Figure 9.3 Predicted changes in temperature for Queensland per degree of warming as modelled by the CSIRO DARLAM-60 regional climate model	154
Figure 9.4 Projected percentage change of rainfall per degree of warming for Queensland.	155
Figure 9.5 Expected return periods for extreme rainfall events for north Queensland as modelled by the CSIRO DARLAM-60 regional climate model	156
Figure 9.6 Monthly actual recordings of maximum and minimum temperature for a) Coen Airport (1970 – 2006) and b) Cooktown Mission Strip (1988 – current).	158
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	159
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)	160
Figure 9.9 Monthly V-wind and U-wind vectors for Princess Charlotte Bay (1980 – 2005)	161
Figure 9.10 Plot of global climate model predicted changes to dry season rainfall.	167
Figure 9.11 Plot of global climate model predicted changes to annual evaporation.	168
Figure 9.12 Time series plot of predicted Princess Charlotte Bay barramundi catch adjusted for effort (CAE) for the suite of climate change scenarios generated	171
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 generated.	171
Figure 9.14 Map of Australian sea surface temperatures (SST) generated by the CSIRO REEFCLIM program for the baseline year of 1995.	173

Figure 10.1	Climate mechanisms that affect north-east Queensland.....	181
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.....	184
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.....	185

LIST OF PLATES

Plate 2.1 Adult barramundi	19
Plate 6.1 MODIS satellite 750 images of Princess Charlotte Bay.....	105