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Sea-Level Change and Demography during the Last Glacial Termination and Early Holocene Across the Australian Continent

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Abstract

Future changes in sea-level are projected to have significant environmental and social impacts, but we have limited understanding of comparable rates of change in the past. Using comprehensive palaeoenvironmental and archaeological datasets, we report the first quantitative model of the timing, spatial extent and pace of sea-level change in the Sahul region between 35-8 ka, and explore its effects on hunter-gatherer populations. Results show that the continental landmass (excluding New Guinea) increased to 9.80 million km^2 during the Last Glacial Maximum (LGM), before a reduction of 2.12 million km^2 (or ~21.6%) to the early Holocene (8 ka). Almost 90% of this inundation occurs during and immediately following Meltwater Pulse (MWP) 1a between 14.6 and 8 ka. The location of coastlines changed on average by 139 km between the LGM and early Holocene, with some areas >300 km, and at a rate of up to 23.7 m per year (~0.6 km land lost every 25-year generation). Spatially, inundation was highly variable, with greatest impacts across the northern half of Australia, while large parts of the east, south and west coastal margins were relatively unaffected. Hunter-gatherer populations remained low throughout (<30,000), but following MWP1a, increasing archaeological use of the landscape, comparable to a four-fold increase in populations, and indicative of large-scale migration away from inundated regions (notably the Bass Strait) are evident. Increasing population density resulting from MWP1a (from 1/655 km^2 to 1/71 km^2) may be implicated in the development of large and complex societies later in the Holocene. Our data support the hypothesis that late Pleistocene coastal populations were low, with use of coastal resources embedded in broad-ranging foraging strategies, and which would have been severely disrupted in some regions and at some time periods by sea-level change outpacing tolerances of mangals and other near-shore ecological communities.

Keywords

Aboriginal Australian demography; Meltwater Pulse 1a; MWP1a; Sahul; Coastal shelf inundation; Radiocarbon ages and modelling; Sea-level change

Highlights

- Investigation of scale, pace and human impacts of post-glacial sea-level change.
- Presents continental-scale consensus sea-level curve for Sahul between 35-8 ka.
- Demonstrates some 2.12 million km^2 (~21.6%) of land lost, notably during MWP-1a.
- Coastlines changed on average by 139 km, and at a rate of up to ~23.7 m per year.
- Populations low, but likely severely disrupted, and led to new configurations.

1. Introduction

The potential impacts of late Pleistocene (<65 ka) sea-level change on Aboriginal populations and societies has long been a subject of speculation by Australian archaeologists and historians. Over four decades ago, Blainey (1975:89–91) hypothesized that: 'In one way or other the rising seas disturbed the life of every Australian for thousands of years. Salt water drowned perhaps one-seventh of the land … Most tribal groups on the coast 18,000 years ago must have slowly lost their entire territory … a succession of retreats must have occurred. The slow exodus of refugees, the sorting out of peoples and the struggle for territories probably led to many deaths as well as new alliances.' This view was recently reiterated by Griffiths (2013:167): 'The advancing coastline pushed people inland, forcing local crowding, the mixing of cultures, and, most likely, causing conflict'.

Archaeologists have long recognised that Aboriginal people would have occupied the now-drowned continental shelves surrounding Australia (Jones, 1968; Lampert and Hughes, 1974; Bowdler, 1977; White and O'Connell, 1982; Dortch, 1996; O'Connell and Allen, 2015), but opinions have been divided about the nature of occupation and the significance of sea-level rise. Mulvaney and Kamminga (1999) argued against widespread evacuations as coastlines advanced, arguing that regions that were most impacted by broad shelves only hosted small populations, while Nunn (2016) and Callaghan (1980) have argued that low-stand coastlines would have been steeply shelving and 'an unattractive prospect for settlement'. More recently, O'Connell and Allen (2015) hypothesized that for a range of ecological and environmental factors, coastal resources would have been quickly depleted by hunter-gatherers and prompted greater use inland prior to the LGM. Similarly, Beaton (1985:17) has proposed that the coasts were little used before the Holocene and that the 'present coasts offer no compelling evidence that they began to receive coastal refugees at any time between 8000 and 5000 thousand years ago'. A similar conclusion was reached for the southeast of Australia by Bowdler (2010). In contrast, Lewis (1988) suggested the opposite, relating sea-level-rise-induced demographic changes in Arnhem Land to alliance-making – symbolised in the appearance of the composite Rainbow Serpent in rock art. Numerous excavations along the west coast of Australia also show exploitation of marine resources by hunter-gatherer populations through the terminal Pleistocene at locations that have always been close to the sea (Morse, 1988, 1993; Przywolnik, 2002, 2005; Veth et al., 2007, 2017). To date, however, these debates have largely been conceptual, and based on limited or no quantitative data. Here, we bring together two comprehensive datasets of past demography and sea-level change for Australia to provide such data, and contribute to the human-sea-level interaction debates.

In the last decade, significant progress has been made in our understanding of past Aboriginal demography. This is in large part the result of continental and regional models of demography and mobility created using radiocarbon data (e.g. Smith et al., 2008; Williams, 2013; Williams et al., 2013, 2015b). The use of radiocarbon data as a proxy for human activity, generally in the form of sum probability or time-series analyses, is an approach first explored in the 1980's (Rick, 1987), and has been further developed and applied in the archaeological literature in Australia and internationally (e.g. Ulm and Hall, 1996; Gamble et al., 2005; Turney and Hobbs, 2006; Surovell et al., 2009; Shennan et al., 2013; Williams, 2013; Timpson et al., 2014). These models show that Pleistocene populations across Australia were strongly influenced by climatic and environmental change (Williams et al., 2015a) which is most strongly expressed during the heightened aridity of the Last Glacial Maximum (LGM) (21±3 ka), when populations appear to fall back into ecological refuges to survive, abandoning large tracts of the continent, and with subsequent egression only in the early Holocene (Veth, 1993; Williams et al., 2013, 2015a; cf. Tobler et al., 2017). While hunter-gatherers can be seen to react to major geo-temporal climatic events in these models, exploration of their response to sea-level change has yet to be undertaken.

As one of the most tectonically stable continents with limited isostatic influence, the Australian continent has been a keystone of Quaternary sea-level studies for over 30 years (e.g. Hopley, 1983; Thom and Roy, 1983, 1985; Woodroffe et al., 1986; Lambeck and Chappell, 2001; Murray-Wallace and Woodroffe, 2014). Recently, a synthesis of this research has been developed as part of the OZ-INTIMATE initiative (Lewis et al., 2013), and provides a consensus view of sea-level change over the last 25,000 years. The synthesis identified that the Australian continent was subject to: i) sea-level that was 125 m lower than present prior to, and during the LGM (see also Ishiwa et al., 2016); ii) a rapid rise between 14.6 and 14.3 ka (MWP1a) followed by a continuing increase through to 8 ka; and, iii) increasing regional variation for the timing and scale of a mid-Holocene high-stand before present levels were attained in the last few thousand years (Sloss et al., 2007, in review; Lewis et al., 2008, 2015; Fogwill et al., 2017). Our study combines these data with additional available sea-level data back to 35 ka (Lambeck et al., 2002) to compare with the archaeological and demographic record.

Here, we explore the interactions and response of past Aboriginal societies to sea-level change at a continental scale. Using established demographic and land-use models with the latest consensus view on sea-level change, we identify how much land was lost to inundation, how rapidly, and consider what effect this may have had on past populations. Given the response of hunter-gatherers to other major geo-temporal impacts over the last 50,000 years (e.g. the mega-aridity of the LGM, and European arrival), we explore the role of changing sea-level on demographic and behavioural change.

2. Materials and Methods

We focus our analysis between 35 and 8 ka, a period of time encompassing the available sea-level consensus data, including the most substantial changes in sea-level since colonization of Australia. This time period also contains a relatively detailed archaeological record, which is limited prior to 35 ka.

Here we use radiocarbon (14C) data from the AustArch dataset as a proxy of past human activity and demographic change (Williams et al., 2014b). The AustArch dataset is the most comprehensive radiocarbon dataset for the Australian continent, comprising 5044 radiocarbon dates from ∼1750 archaeological sites. Of these, 951 ages from 322 sites are from the period 35–8 ka. The archaeological data come from a range of site types, including rockshelters, open sites, middens, fish traps, and burials, and includes both terrestrial and marine samples. There have been a small number of additional sites dated to the 35–8 ka interval reported since the publication of AustArch, most notably Boodie Cave (WA) (Veth et al., 2017) and Warratyi rockshelter (SA) (Hamm et al., 2016), but these do not affect the overall trends of the dataset, and have been incorporated in the discussion and figures where relevant.

For palaeo-populations, we re-ran demographic models developed by Williams (2013). These used statistical transformation of the AustArch dataset to develop annual percentage growth rates (GRAnn) or birth rates, and quantitative estimates of hunter-gatherer numbers across Australia at 200 year intervals over the last 50 ka (see Supplementary Data). We also explore the amount of land utilized by past populations through time using a cluster analysis and minimum bounding rectangle approach developed by Williams et al. (2013) and (2015a) (see Supplementary Data). This analysis defines spatially bounded radiocarbon data from similar time periods to provide quantitative estimates of areas or territories occupied by hunter-gatherers. When combined across Australia, the data provide an overall indication of the amount of land used, and an indirect proxy for mobility of past populations.

To determine sea-level change, we used data from the continent-wide curve compiled from several sea-level proxies (including mangrove mud/peat/wood, wood, peat, corals, shell material, ooids and foraminifera) by Lewis et al. (2013). We pre-appended the sea-level data from Lambeck et al. (2002) to extend this synthesis to 35,000 years. Specifically, we interpolated a line of best fit through the estuarine indicators (i.e. mangrove material, intertidal bivalves) and between the terrestrial (wood, peat - i.e. relative sea-level lower than terrestrial indicators) and marine (coral, shell/carbonate material, foraminifera and ooids - i.e. relative sea-level higher than marine indicators) proxies to report data at 200-year intervals (as metres below relative present mean sea-level (PMSL) between 35 and 8 ka. This line of best fit falls within the sea-level envelope produced by Lewis et al. (2013) (see Supplementary Data). Whilst the envelope is variable in terms of uncertainties, we highlight that the most significant change in sea-level in the terminal Pleistocene, MWP1a (14.6–14.3 ka), is well defined in the dataset, with relatively small uncertainties (±∼5 m).

To calculate the loss of land by sea-level rise through time, we applied the interpolated values to the Australian Bathymetry and Topography Grid (ABTG) dataset (Whiteway, 2009) using ArcGIS. ABTG is a raster dataset of Australia and the surrounding continental shelf at a 9 arc-second (∼250 m) resolution. Our analysis constrained the ABTG dataset to vertical values of −125 to 0 m PMSL, and spatially to the entire Australia continent (8–45°S), off-shore islands and continental shelf, and stopping at the southern New Guinea coastline. Bathymetric data for New Guinea is sparse, with ABTG not extending north of 8°S, and limiting analysis further north. Genomic data also show that interactions between Australia and New Guinea were limited after colonization (Tobler et al., 2017). We further highlight that our data include much of the Arafura plain, with most of the remaining New Guinea coastline having extremely steep crustal shelves (Chappell, 2005), and so would have been minimally affected by sea-level change. Therefore adding ∼780,000 km^2 for New Guinea to our calculations would largely address this omission for researchers that require its inclusion. For each 200-year interval, the area of the continent was calculated once the respective relative sea-level was applied, the difference in landmass between intervals was then determined to identify a gain or loss of land over a given time period. Finally, we adopted the methods of Anderson and Bissett (2015) to determine the speed of sea-level rise by measuring the changing distances between each shoreline at given time intervals, at selected locations around the continent during the terminal Pleistocene.

2.1 Limitations

2.1.1. Archaeological Data

Despite repeat and often groundless criticism (e.g. Attenbrow and Hiscock, 2015; Torfing, 2015; Hughes et al., 2017), use of radiocarbon data as an archaeological proxy is arguably one of the most robustly interrogated techniques applied to the investigation of past human activity. Since the identification of a range of potential issues with its application by Williams (2012), there have been a plethora of publications identifying limitations and providing techniques to counter or correct them. These include exploring and addressing the applicability of radiocarbon samples to reflect human activity and/or demographic change (Williams et al., 2015a, 2015b), sample size and bias (e.g. Shennan et al., 2013; Timpson et al., 2014), calibration effects (e.g. Brown, 2015; Weninger et al., 2015; Crema et al., 2016), and time-dependent taphonomic loss (Surovell et al., 2009; Kelly et al., 2013), as well as increasingly advanced issues such as spatial and/or temporal differences in site-to-population ratios (e.g. Downey et al., 2014) and sampling intensity (e.g. Crema et al., 2016).

Here we highlight two limitations of the technique pertinent to our analysis, and which cannot be readily corrected: sample size and spatial bias, and taphonomic loss. Despite the authors (AW and SU) compiling a substantial published and extensive unpublished archaeological radiocarbon dataset for the Australian continent, few data fall between 35-8 ka. The results produced here will, therefore, not be as robust as similar types of analysis in other regions such as Europe or North America, and/or for later periods in the Holocene in Australia where more data are available. Further, the distribution of radiocarbon data across Australia is strongly influenced by areas of academic interest and/or development driven cultural resource management (CRM). This has resulted in some areas with significant data, such as the southeast corner of Australia (where much of the contemporary population are situated and CRM work is extensive), compared with other parts that have few documented sites. The absence of data in a location may therefore reflect an absence of past activity, but could also be a lack of archaeological investigation to date. This is especially the case for many parts of the arid interior and along the Kimberley coastline, where accessibility has limited research opportunities. Conversely, areas in the southeast corner and east coast of Australia are well studied, and the results here can be considered highly robust in these regions (Langley et al., 2011).

Taphonomic bias is the over-representation of younger sites due to the loss of older sites from environmental and climatic factors. It can also be considered to encompass differential preservation of archaeological sites due to such factors, e.g. the difference between the alkaline limestone karsts of Cape Range (where shell assemblages are well represented) compared with the more-aggressively weathering sandstone geology along the east coast of Australia. While statistical techniques have been developed to account for taphonomic loss for time-dependent radiocarbon time-series outputs, there is currently no way to apply such correction spatially. We must therefore acknowledge that taphonomic bias is a potential limitation of the study, and an absence of data may be a result of these processes, rather than necessarily a lack of past human populations.

2.1.2. Sea-Level Reconstruction

Here we use a line of best fit to provide a single value for sea-level change through time. We highlight, however, that sea-level indices generally include errors and/or provide a range of potential values, and as such the line of best fit may be inaccurate in some spatial and/or chronological areas. There is a high level of uncertainty in the sea-level reconstruction between 35 and 22 ka with sparse data-points and less reliable sea-level indicators, which are made up of a combination of marine and terrestrial indicators (i.e. not the more precise estuarine/intertidal indicators - see Supplementary Data). From 22 to 8 ka, a combination of more reliable estuarine/intertidal, marine and terrestrial sea-level indicators are available with key locations such as the Sunda Shelf (Hanebuth et al., 2000, 2009), Joseph Bonaparte Gulf (Yokoyama et al., 2000, 2001) and Huon Peninsula (Chappell and Polach, 1991; Edwards et al., 1993; Ota and Chappell, 1999) particularly informing the sea-level curve. However, the indicators from these key sites are still subject to uncertainties (refer to individual references provided and a review of individual indicators in Lewis et al., 2013). Indeed, the Huon Peninsula site is subject to apparently constant tectonic uplift which has been corrected for in the dataset (e.g. Chappell et al., 1996), although no such correction has been applied for the remaining data where we cannot rule out the possibility of localized/regional uplift or subsidence (see Bryant, 1992; Lewis et al., 2013). In that regard, the relatively tight agreement of the sea-level indicator data between 22 and 8 ka from several locations suggests that the tectonic influence in this region was relatively minor, and provides confidence in the data selected for this study.

3. Results and Discussion

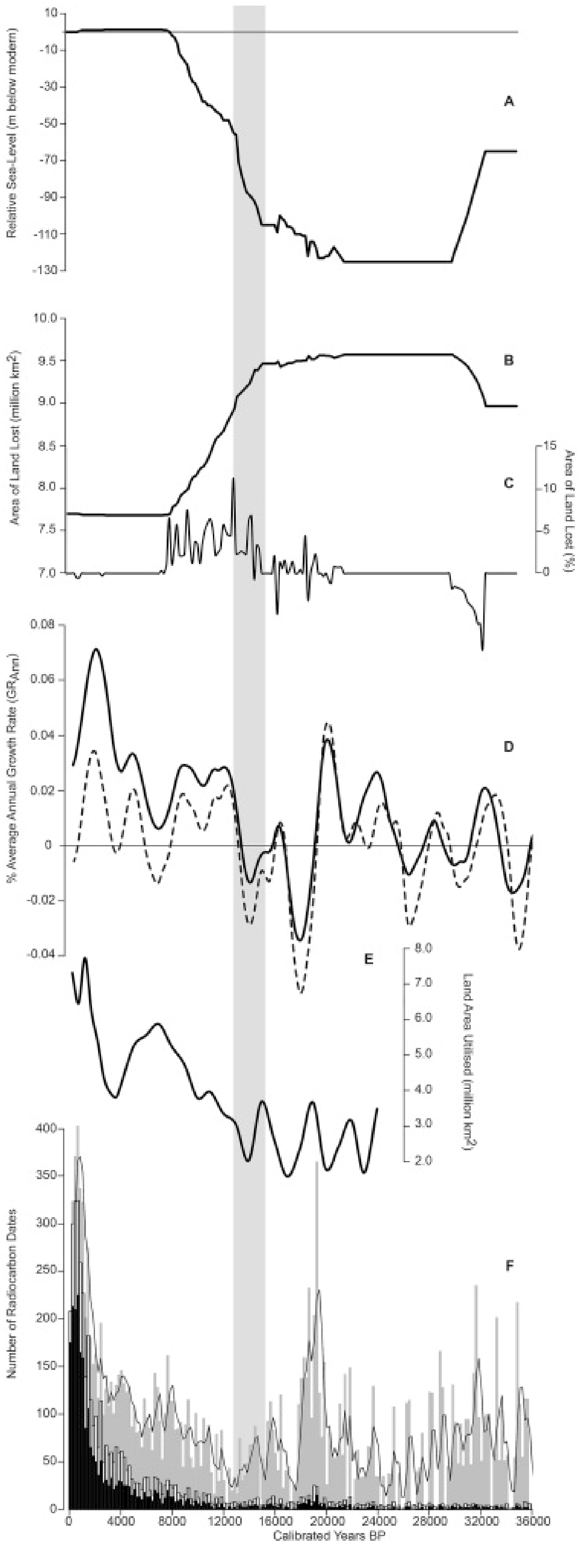
3.1. A Continental Perspective

Our results show that at 35 ka the continental landmass (excluding New Guinea) was 9.11 million km^2, increasing to 9.80 million km^2 at the onset of the LGM when sea-level dropped from −65 to −125 m PMSL (between 32.6 and 29.8 ka) (Figs. 1 and 2; Table 1). By 8 ka, however, rising sea levels accompanying global deglaciation, Australia was 7.68 million km^2, a reduction of 1.43 million km^2 (or ~15.9%) relative to the 35 ka landmass, or 2.12 million km^2 (or ~21.6%) compared to the LGM. The most substantial changes in continental landmass occurred during declining sea-levels at the onset of the LGM, resulting in a gain of ~0.6 million km^2, and the rapid loss of land during and following MWP1a, with over 1.9 million km^2 inundated between 14.6 and 8 ka (Fig. 1).

Table 1. Changing sea-level, continental landmass, Aboriginal populations and density for selected time periods. Aboriginal populations are based on models from Williams (2013) (uncorrected radiocarbon data; founding population of 2500 at 50 ka; and a smoothing spline with 50 d.f.). See Supplementary Data for the full dataset and further details.

Date (ka)	Relative Sea-level (m PMSL)	Continental Landmass (million km^2)	Change from Previous Time Interval		Population (000's)	Population (1/n km^2)
			(million km^2)	(%)		
35	−65	9.11	–	–	13.9	655
29	−125	9.80	0.69	7.57	12.6	778
21	−119	9.77	−0.03	−0.31	21.5	454
17	−103	9.67	−0.1	−1.02	22.8	424
15	−100	9.64	−0.03	−0.31	28.6	337
13	−64	9.08	−0.56	−5.81	23.7	383
11	−42	8.44	−0.64	−7.05	47.9	176
8	0	7.68	−0.76	−9.00	107.9	71
Total			−1.43	−15.93		

Between 35 and 13 ka, hunter-gatherer populations were at some of their lowest throughout the last 50,000 years, averaging ~20,500 individuals at any given time interval (Table 1), before a dramatic step-wise increase during the Holocene that culminated in an estimated ~1.2 million by 0.5 ka (Fig. 1) (Williams, 2013; Malaspinas et al., 2016; Tobler et al., 2017). The population rise into, and through, the Holocene began immediately following MWP1a. After a small decline between 15 and 13 ka – perhaps reflecting the direct impact of the sea-level rise on populations – we observe a four-fold increase in hunter-gatherer numbers at the late Pleistocene/Holocene transition (with ~24,000 at 13 ka compared to ~110,000 at 8 ka) (Table 1). While an increase in numbers continued after 8 ka, it was at a much slower pace until the mid-to-late Holocene (~4.5–5 ka) (Williams, 2013), strongly suggesting that the population explosion observed immediately after MWP1a (an occurrence not seen a considerable time before or after this event) is associated with the migration and spatial contraction of hunter-gatherers in response to the inundation. Given this rise of population over a ~5000 year period (13–8 ka), our data indicate that the impact of MWP1a had a lasting effect, and resulted in significant re-organisation of land use and societies during this time (Lourandos, 1997; Smith, 2013; Williams et al., 2015a, 2015b; Malaspinas et al., 2016).



Relative Sea-Level (m below modern)
A
Area of Land Lost (million km2)
B
C
Area of Land Lost (%)
% Average Annual Growth Rate (GRAnn)
D
E
Land Area Utilised (million km2)
Number of Radiocarbon Dates
F
Calibrated Years BP

Figure 1. Aboriginal demography and mobility, and sea-level change between 35-8 ka. A) Sea-level change adapted from data in Lewis et al. (2013) and Lambeck et al. (2002), presented as relative metres below present mean sea-level (PMSL); B) The amount of landmass lost as a result of sea-level change between each time interval based on bathymetric data; C) As (B), but presented as a percentage change from the previous time interval; D) Average annual growth rates (GRAnn) from Williams (2013) using both uncorrected (solid black line) and taphonomically corrected (dashed line) radiocarbon data; E) Total ranging areas by hunter-gatherers using data in Williams et al. (2013) and (2015a). F) Numbers of radiocarbon dates adapted from Williams (2013) providing qualitative changes in Aboriginal demography. The uncorrected radiocarbon data are presented as a stacked bar chart of uncorrected calibrated data (white = open sites; black = closed/rockshelter sites). Two methods of taphonomic data correction are presented – corrected open site data and uncorrected closed/ rockshelter site data after methods in Williams (2013) (dark grey) – a 600 year trendline (black) is also included for these data; and both open and closed/rockshelter site data corrected after methods in Williams (2012) (pale grey bars). Further details of all methods are presented in Supplementary Data. Meltwater Pulse 1a is presented as the grey shading extending across the stacked figure. Note periods after 8 ka have been presented to provide context, but have not been used in the analysis.

The shrinking land mass also reinforced the impact of hunter-gatherer migration through increased population packing (Binford, 2001). Prior to the LGM, populations were at ∼1 person/600–700 km^2 (Table 1), and while being tethered to broad geographic regions, were mobile within sub-regions ('nomadic sedentism') (Meggitt, 1962; Gould, 1977; Tonkinson, 1978; Smith, 2013; Williams, 2013; Tobler et al., 2017); a situation that continued through the LGM and into the termination of the Pleistocene (Reeves et al., 2013; Turney et al., 2006), with the adoption of point-to-point strategies and use of cryptic refuges (Veth, 1993; Smith, 2013; Williams et al., 2013, 2014a; Tobler et al., 2017). (Cryptic refugia are isolated or scattered pockets of ecological biota within which people can survive, effectively a thinning of population across the entire landscape, rather than the more commonly held view of substantial parts of Australia being inhabitable; point-to-point strategy is the mechanism by which people move between these isolated pockets of ecological biota to survive, rather than home-base strategies where they are tethered to a single point). However, by the Pleistocene/Holocene transition, populations steadily increased to 1 person/180 km^2 immediately after MWP1a, and 1 person/70 km^2 by 8 ka. Based on analysis by Williams et al. (2015b), it seems unlikely that these values would have resulted in environmental filling of the continent, which was not evident until ∼6 ka (when populations were at ∼1/50 km^2 or higher) (Fig. 1), but would likely have begun to reduce mobility and patch choice, and represented the first indications of a more sedentary population observed later in the Holocene. This situation may have been accelerated with the loss of land area from the top end of Australia, which was likely some of the most environmentally productive (Balme et al., 2009: Fig. 4). MWP1a may have, therefore, provided the broad driver for the expansion of hunter-gatherers from Pleistocene ecological refuges as proposed by Williams et al. (2015b), and ultimately led to population increase across the Holocene. The contraction and resulting closer interactions of populations following this event also provide a plausible mechanism for the differentiation and spread of Karrwan-Tangkic-Pama Nyungan languages proposed to have occurred in the early Holocene (McConvell, 1990; Smith, 2013; Malaspinas et al., 2016). By 8 ka, increasing numbers of new archaeological sites are established, many for the first time (Fig. 2). We highlight that many of these sites appear along shorelines that were subject to relatively minor inundation (e.g. New South Wales), and suggest sea-level change was not a direct driver of occupation in some parts of Australia, but more likely indirectly through demographic packing and/or other socio-economic driver (see Williams et al., 2015a for discussion).

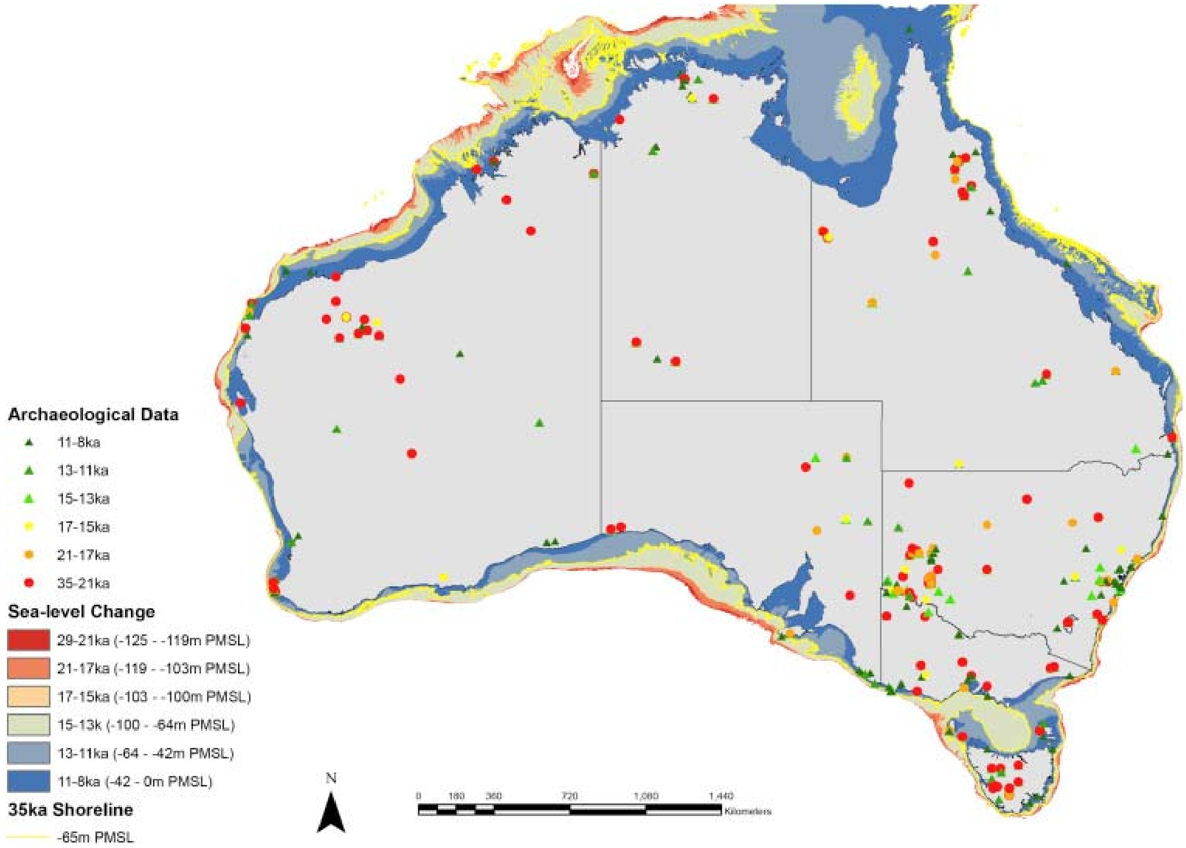


Figure 2. Map of Australia showing major sea-level change and archaeological sites presented by selected time-slices between 35-8 ka. Archaeological data presented consists of median calibrated ages of radiocarbon dates from AustArch (Williams et al., 2014b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Spatial Impacts of Inundation

Spatially, late Pleistocene rising sea-level resulted in substantial changes to the continental coastline (Fig. 2). This is most evident along the entire northern fringe of the continent from Cape Range in the mid-west across to Princess Charlotte Bay in the northeast, and incorporating the Kimberley, Arnhem Land, Gulf of Carpentaria and Cape York. Distances between the LGM and 8 ka coastlines are on average ∼139 km different, with several areas >200 km (e.g. Dampier Peninsula), and >300 km in the vicinity of Cambridge Gulf, Keep River, and Daly River (Table 2) (geographic locations presented in Supplementary Data). The basin of the Gulf of Carpentaria also sees changes of several hundred kilometres, but likely has a far more complex history with a land-bridge between Arnhem Land and southern New Guinea (the Arafura Sill) delaying inundation until ∼13 ka, after which it most probably in-filled rapidly (see also Reeves et al., 2008) (Fig. 2). Elsewhere, large parts of the crustal shelf from southeast and central Queensland lost between 50 and 150 km, while the southern fringe - between Cape Le Grand to Mount Gambier – experienced similar inundations of >150 km and >300 km within the Australian Bight (Table 2; Supplementary Data). Given hunter-gatherer's territories were on average ∼450 km^2 based on ethnographic observations (e.g. Marlowe, 2005), distances of >30 km, would likely have resulted in significant impacts to past populations. Between 35 and 15 ka, archaeological sites are closely linked with ecological refuges usually associated with glaciated uplands and/or major river systems (Veth, 1993; Williams et al., 2013), and there is no clear evidence of widespread impacts of sea-level changes (Fig. 2). However, where such sites are present on the coastline, they are generally found in locations where shoreline change has been relatively limited (Fig. 2), including southwest Western Australia, Cape Range, Barrow Island, Kangaroo Island, Cape Bridgewater, and the New South Wales coast (Lourandos, 1983; Draper, 1987; Morse, 1988, 1993; Godfrey et al., 1996; O'Connor, 1999; Przywolnik, 2002, 2005; Richards, 2012; Veth et al., 2017). While the sample size is small, it does suggest that pre-LGM and LGM hunter-gatherers were undertaking at least some exploitation of coastal resources, and preferentially occupied sites where the crustal shelf was narrow, and the littoral zone least affected by sea-level change (Callaghan, 1980; O'Connell and Allen, 2015; Veth et al., 2017).

Our data also reveal the extensive and complex inundation of the Bass Strait, with flooding beginning in the west at 15 ka, and leaving an ever-narrowing eastern land-bridge until 11 ka when the island of Tasmania was isolated (Figs. 2 and 3). This finding correlates well with a model previously published by Lambeck and Chappell (2001), although our data suggest the event occurred much later than they proposed (15–11 ka versus 17.5–14 ka), possibly due to improving sea-level and bathymetric data, and regional isostatic influences. This later age range corresponds more closely with the archaeological records in Tasmania, which show clear disruption of hunter-gatherer populations between ∼16 and 13 ka, and dominance of coastal exploitation after 9 ka (Bowdler, 1984, 2010; Colley and Jones, 1987; Williams et al., 2015a).

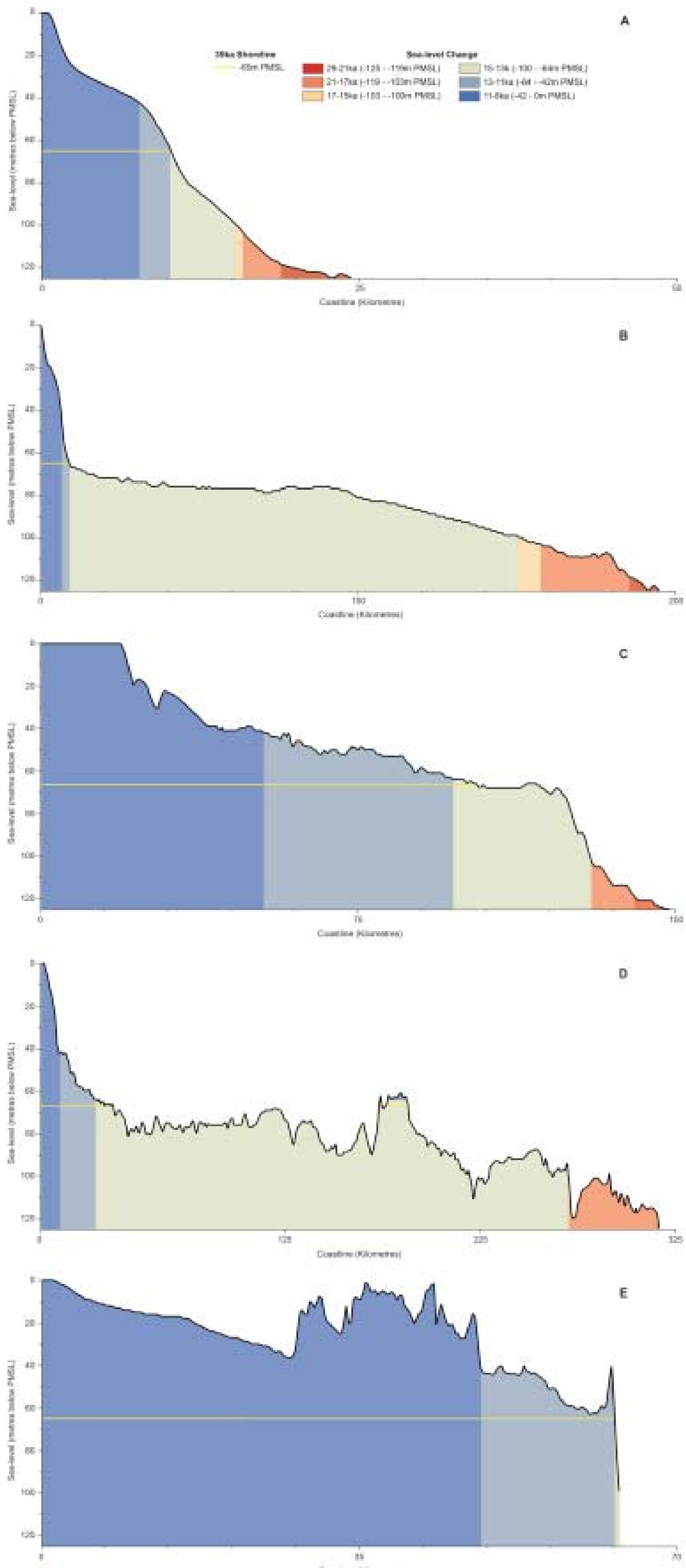
Along with rapid global sea-level rise, the geomorphology and topography of the crustal shelf also played a significant role in coastal development. Much of the crustal shelf is situated between ∼ −80 to −40 m PMSL (1.01 million km^2), elevations that were only reached just prior to, and during the MWP1a, resulting in a much greater spatial impact than sea-level rise alone (Fig. 3). This has the important implication of leaving many of the contemporary off-shore islands land-locked for much of the terminal Pleistocene (until <13 ka), including Tasmania, King Island, Flinders Island, Kangaroo Island, Tiwi Islands, Groote Eylandt, Wellesley Islands, the Torres Strait Islands, Lizard Island Group, Whitsunday Island Group, Fraser Island, Moreton Island, North Stradbroke Island, and Barrow Island (Fig. 2, Supplementary Data). Several of these archipelagos would likely have formed prominent high ground on the landscape, and given the pace of inundation (see below), may have formed important locations, or micro-refuges, for hunter-gatherers during the late Pleistocene (see also Brooke et al., 2017). Tangible evidence for this is documented at Boodie Cave on Barrow Island with occupation extending back to ~46–51 ka despite being some distance (>10 km) from the coast until the Holocene (Veth et al., 2017). The favourable preservation conditions at Boodie Cave provides one of the longest faunal records in Australia. In the earliest cultural deposits dating to ~46-51 ka when the coast is some distance away, there are only four different types of shell, including nerites – one of the few species that remain fresh for several days after collection. Following the LGM as the coastline gets closer to the cave, the number and variety of marine resources increases exponentially, with 40 different types of marine shells as well as sea urchins, fish, snakes and euros by the early Holocene. Sea-level change prior to MWP1a was likely constrained by the steep slopes/cliffs along the edge of the crustal shelf (Fig. 3), limiting land loss in many areas between ~29.8 and 15 ka. Before sea-level rise breached the continental shelf, the northeastern coastline may have contained massive freshwater lagoon systems where karstified hills along the continental margin (formed by previous coral reef growth during high-stands) blocked incision of rivers to the outer shelf (Woolfe et al., 1998; Dunbar and Dickens, 2003). By the end of the Pleistocene, the continental coastline was largely established, and saw little significant change through the Holocene. It is after this time that large numbers of archaeological sites appear along the coastal fringe, especially on the southeast coast and newly formed Bass Strait (Fig.

2).

While, several parts of the continent are subject to large changes, a number of areas remained relatively unaffected during the late Pleistocene. Only Cape Range has remained adjacent to the coastline (~5 km) throughout 35–8 ka, but a number of locations were <15 km from the contemporary coastlines across the same time period, including Dirk Hartog Island, Cape Bridgewater, Cape Howe, and Jervis Bay (Fig. 2). In addition, much of the New South Wales, Victorian and southwest Western Australia coastlines only changed by ~20–40 km through the LGM into the early Holocene (Fig. 3). These distances are well within a hunter-gatherer's typical foraging range of ~14–20 km per day (e.g. Gould, 1977; O'Connell and Hawkes, 1984; Marlowe, 2005; Pontzer et al., 2012), and which would have encompassed both the Pleistocene coastlines and hinterland – the latter now part of the contemporary coastal fringe. As such, coastal impacts from sea-level change in these areas was considerably less than other parts of the continent. Observation of contemporary Australian hunter-gatherers show that the marine resources form only a small part of the diet (<20%) (Meehan, 1982), and archaeologically we see similar evidence of coastal-hinterland economies throughout the terminal Pleistocene (e.g. Jansz and C99 rockshelters (Przywolnik, 2002, 2005), and Boodie Cave (Veth et al., 2017)). We should, therefore, find an extensive archaeological record in these hinterland regions from exploitation of terrestrial resources if populations were substantially present. However, this does not appear to be the case (Fig. 2), and indicates that the absence of pre-8 ka archaeological sites in many of these regions is not necessarily a result of taphonomic loss through inundation (e.g. Hiscock, 2008), but rather reflects low intensity occupation and use (as proposed by Mulvaney and Kamminga, 1999; Bowdler, 2010; and O'Connell and Allen, 2015).

Table 2. Shore-line movements (metres) between 35-8 ka, calculated from 35 transects around the continent (full details of the transects are presented in Supplementary Data). Average, maximum, and minimum values are presented, along with changes per generation (25 years) and annually.

	Time interval (ka)							**Overall Shoreline Change between**		
	35–29	29–21	21–17	17–15	15–13	13–11	11–8	35-8 ka	29-8 ka	15-8 ka
Maximum	290,833	−15,308	−58,801	−17,552	−260,566	−241,271	−182,957	−373,237	−460,618	−460,618
Minimum	303	−212	−359	−174	−316	−1010	−1842	−2059	−5163	−4064
Average	56,920	−3763	−11,324	−2583	−47,335	−40,144	−40,352	−82,660	−139,580	−124,185
Average movement per generation	203.29	−11.76	−70.77	−32.28	−591.68	−501.81	−336.27	−76.54	−166.17	−443.52
Average movement per year	8.13	−0.47	−2.83	−1.29	−23.67	−20.07	−13.45	−3.06	−6.65	−17.74



A
Sea-level Change
B
C
D
E

Figure 3. Cross-section profiles of the crustal shelf along selected transects: A) Port Stephens, NSW; B) Cape Otway, VIC; C) Pilbara coastline, WA; D) Kalumburu, WA; and E) Cooktown, QLD. Time-intervals of sea-level inundation are presented as colour shading. Note differing horizontal axis reflecting the differences in continental shelf width. Further details of these transects are presented in Supplementary Data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. The Pace of Inundation

Shoreline movements indicate that the speed of coastal change prior to the LGM (35–29 ka) was fairly rapid, with horizontal/lateral gains of ∼8 m per year (Table 2). Since sea-level change in this interval primarily occurred between 32.6 and 29 ka, this change was likely closer to ∼14 m per year (or ∼350 m per generation). While resulting in large gains in land, in the short-term such adjustment would have led to significant disruption of coastal resources, with established ecosystems left stranded as the water receded, and this may account for the increasing appearance of archaeological sites exploiting inland environments, especially major water tributaries, through this period (see also O'Connell and Allen, 2015; Bird et al., 2016). For instance, visitation along the Hawkesbury River (PT-12), Gregory River (Gregory 8 rockshelter), Gilbert River (Gledswood 1 rockshelter), Fitzroy River (Carpenters Gap 1 rockshelter), and Fortescue River (Juukan-1 rockshelter) (see Supplementary Data for location and references) all began at this time. The earliest deposits at Noala Cave (Montebello Islands), a brief visitation at ∼30 ka, revealed hunter-gatherers exploiting terrestrial resources, despite being only ∼40 km from the coastline (Veth, 1995; Veth et al., 2007). During the LGM, sea-level was relatively stable, and changes to the shoreline minor, perhaps only 0.5–3 m per year, equating to ∼12–71 m per generation. Such distances would have been essentially negligible to highly mobile hunter-gatherers, who were at a population nadir at that time (Table 1) (Williams, 2013). Where the coast was accessible, it was generally steep and would have retained attractive littoral habitats (Ulm, 2011; O'Connell and Allen, 2015; cf. Callaghan, 1980). In the Bonaparte Gulf in northwest Australia, Ishiwa et al. (2016) show that only soft bottom shellfish (such as Anadara sp. and associated taxa) are represented during a falling sea-level phase at ∼30.5 ka, but a much broader suite of shellfish was recovered during the relatively stable LGM, before deepening transgressive waters after 18 ka saw a loss of these taxa in the record. Exploitation of marine resources continued at some sites across the LGM (e.g. Pilgonaman rockshelter, Bass Point, Cliff Cave, Seton Site, Boodie Cave) (see Supplementary Data for location and references), but the focus of occupation remained in the interior (Fig. 2) (see Williams et al., 2013 for discussion).

Following the LGM and into the early Holocene, sea-level transgression was inundating the coastline at a rate of ∼13–24 m per year, or ∼0.5 km per generation (Table 2). Along parts of the northwest shelf (Kimberley, western Northern Territory), these values increased in some areas to >130 m per year, or ∼3 km per generation, with an average of ∼80 m per year (~2 km per generation) between 15 and 8 ka. Such changes would have resulted in dramatic coastal disruption, notably the changing distribution of productive shell beds and mangals (Callaghan, 1980; Beaton, 1995; O'Connell and Allen, 2015). Recent hypotheses on the scale of these impacts have focused on the available sedimentary substrate supporting or constraining mangal development through this time interval (Ward et al., 2013; O'Connell and Allen, 2015). However, studies of contemporary mangals show that they typically occupied the edge of tolerance limits, and prolonged sea-level change of >12 cm/100 years would have resulted in collapse of these communities (Ellison and Stoddart, 1991; Kathiresan and Bingham, 2001; Duke et al., 2017) – values that were substantially exceeded on an annual basis between 15 and 8 ka. Such a rapidly changing shoreline would similarly have affected the establishment and growth of shell beds, which while no doubt present were also likely struggling with the fluctuating conditions. It is acknowledged that there were local refuges of mangal as suggested by Ward et al. (2013) and d'Alpoim Guedes et al. (2016), and perhaps best represented in the archaeological record at Cape Range, Carnarvon and coastal Pilbara where Terebralia species (which preferentially lives in mangals) were exploited throughout the Pleistocene/Holocene transition (Przywolnik, 2002, 2005; Smith, 2013; Veth et al., 2017). Brooke et al. (2017) have also shown the micro-topography of terminal Pleistocene coastal fringe would have been highly diverse. However, overall, the potential for established mangals across much of the continental shelf would have been limited for most of the terminal Pleistocene, until sea-level rise flooded the shelf, and after the rapid rise associated with MWP1a. Archaeologically, this would likely have resulted in a shift to exploitation of more terrestrial resources, and a number of inland sites become established and/or active at this time (15–8 ka) (e.g. Walga rockshelter, Puntutjarpa rockshelter, Mickey Springs 34, Gordolya rockshelter, Native Well 1, and JSN Site) (Fig. 2) (see Supplementary Data for location and references). There is no evidence for any significant exploitation of the coastline, with the exception of those sites that were always in close proximity to the coastal fringe, such as at Cape Range (Morse, 1993; Przywolnik, 2002, 2005) and the Pilbara (Veth et al., 2017) – mainly sites that were also constrained by arid or desert environments to the east, and provided little other alternative resources to hunter-gatherers in these regions. Indeed, the sheer pace of the inundation would have made any long-term or repeated occupation virtually impossible, and it, again, raises the potential importance of high ground and promontories (later to become offshore islands), for hunter-gatherers to have been able to develop any form of prolonged or extended occupation in such active environments.

As sea-level stabilized at 8 ka, and shoreline resources become stabilized and/or more prevalent, an increasing number of archaeological sites became established on the contemporary coastline. Notably, these sites are overwhelmingly located around the southeast coastline (between Cape Jaffa and Newcastle), north Tasmania, King and Flinders Islands, and along the northwestern coastline (between Cape Range and western Arnhem Land) (Fig. 2) – all regions that would have been the most affected by population migration from the inundated areas of the Bass Strait and Timor Sea. The recent findings of stone huts dating to ~8–9 ka and indicative of low mobility occupation on Rosemary Island (WA) (McDonald and Berry, 2016) may provide some of the first archaeological evidence that these peoples and/or land use re-organisation may have resulted. It is interesting to speculate whether the large populations observed in the southeast later during the Holocene (Williams et al., 2015a) may have begun as a result of packing thresholds and environmental filling, at least in part, from migrants of Tasmania and the inundated Bass Strait, and the Australian Bight, into the southeast corner of Australia. While archaeological data across the northwest and north of Australia are sparse, a similar story of population contraction and subsequent growth, hinted at in the numerous non-Pama Nyungan language groups in the Kimberley and Arnhemland and by recent finds at Boodie Cave, may also be evident in years to come.

4. Conclusions

Using comprehensive datasets of Aboriginal demographic reconstruction and sea-level change, and applying advanced geospatial techniques, we explore human-sea-level interactions through the terminal Pleistocene. For over four decades, it has been widely known that sea-level transgression along the Australian coastline was extensive, but the impacts upon past populations has been widely contested. For the first time, we present a quantitative study of the timing, spatial extent and pace of sea-level change between 35 and 8 ka, and the effect this significant geo-environmental event had upon hunter-gatherer populations.

We show that following initial gains of ~0.6 million km^2 as sea-level dropped at the onset of the LGM, subsequent inundation resulted in the eventual loss of 2.12 million km^2 of the coastal fringe by the early Holocene – equivalent to ~21.6% of the LGM continental landmass (excluding New Guinea). Some 1.9 million km^2 of this submerged landscape was lost during, and immediately following MWP1a, between 14.6 and 8 ka. Coastlines between the LGM and early Holocene changed on average by ~139 km, with some areas >300 km, and at a pace of up to 23.7 m per year (~0.6 km per 25-year generation). However, spatially, the effects of the inundation were disparate, with the greatest impact across the northern half of Australia and the flooding of Bass Strait, while substantial parts of the southeast, east, southwest and west remained relatively unaffected. These impacts would have had significant impacts to environmental productivity, with the lands across the northern half of Australia likely far more important to hunter-gatherers than other sectors of the continent (Balme et al., 2009). Hunter-gatherer populations remained low throughout the terminal Pleistocene, but responses to sea-level change are evident, including an increasing utilization of inland and riverine environments at ~35–30 ka as coastline recession disrupted marine resources, and a four-fold increase immediately following MWP1a. This rapid population increase, in tandem with large numbers of archaeological sites being established around the southeast and northwest parts of the continent, strongly suggests that the data reflects migration of hunter-gatherers inland from the recently submerged crustal shelf. The resulting population densities, along with improving climatic conditions between 9 and 6 ka, may be associated with the appearance of increasingly large and complex Aboriginal societies observed in the Holocene archaeological record (see Williams et al., 2015b for discussion).

Our analysis questions whether the coastal fringe was a primary focus for hunter-gatherer occupation and use prior to the Holocene (Beaton, 1985; Mulvaney and Kamminga, 1999; cf. Bowdler, 1977). Both anthropological and archaeological evidence reveal that in most regions only a small portion of the Australian hunter-gatherer diet was reliant on marine resources, yet in areas where sea-level change was relatively small, and the hinterland of the terminal Pleistocene coastline can still be interrogated, we fail to find evidence of terrestrial-based activities. Furthermore, coastal productivity throughout the terminal Pleistocene was also potentially very poor, with the sheer pace of sea-level change constraining mangal and shell bed distribution. While, it is acknowledged that a number of archaeological sites demonstrate ongoing use and exploitation of marine resources throughout the terminal Pleistocene, most notably in Carnarvon and coastal Pilbara regions, these are all on steep crustal shelves where coastal productivity may have been less affected by sea-level change, and often in arid environments where alternative resources may have proved more elusive.

4.1. Future Directions

Our study identifies a number of areas for future research. We acknowledge that findings and conclusions of this paper are based on limited archaeological data, especially across the top end of Australia. Rather than providing definitive conclusions, it therefore provides a range of hypotheses and questions for testing and investigation.

At a continental scale, the inclusion of New Guinea and its surrounds is desirable to provide complete coverage of Sahul – developing a well-resolved spatial dataset of the crustal shelf for New Guinea is essential to achieve this. Investigation and/or re-investigation of sites along the southern Australian and northern Tasmania coastlines should be undertaken to explore the commonalities in timing of occupation, technologies and other attributes to determine whether tangible evidence of the early Holocene migration suggested here is supported. A similar investigation of areas to the northwest should also be undertaken, with archaeological data in these areas fairly sparse. Further investigation of Dirk Hartog Island, Cape Range, Cape Bridgewater, Cape Howe, and Jervis Bay, all situated close to the coastline throughout the terminal Pleistocene, may also provide a greater understanding of marine and terrestrial exploitation in a range of ecotones.

Given the pace of the sea-level inundation, dense or long-term occupation sites were likely limited to elevated landscapes, promontories and/or other headlands, the permanence of which may have been attractive to hunter-gatherers despite their changing distance to the coastline. In contrast to other coastal sites, such features should form a focus for future archaeological investigation since they may provide more complete records of the past (e.g. Boodie Cave).

Finally, it seems highly probable that the continental shelves would have been occupied, albeit by low density populations, creating the potential for the recovery of submerged archaeological remains, and should form a target for future research to document this crucial period in Australia's human and environmental history.

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