October 1992

Last interglacial and Holocene trends in sea-level maxima around Australia: Implications for modern rates

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Abstract

This paper defines the spatial trend in sea-level around Australia at 3 timescales, namely at the time of the maximum of the last interglacial around 125000 yr BP, during the Holocene maximum between 5-6000 yr BP and over the last 20 years. Last interglacial elevations range from -2m around the Great Barrier Reef to +32m in northeast Tasmania. Trend surface analysis shows that over 77% of the noise in these sea-level elevations can be accounted for by a pattern evidencing tectonic uplift towards the southern edge of the continent. Assuming a eustatic sea-level at this time of +4 to 6m, most of the east coast of New South Wales and the west coast of Western Australia can be considered tectonically stable, while the southern edge of the continent has risen by at least 5m and the north-northeast corner has downwarped by at least 2m. The spatial pattern of the Holocene maximum tentatively supports the continuation of this tectonic deformation. Sea-level at this time reached 1.6m and 2.4m above present high tide limits around the northern and southeastern coastlines of Australia respectively. This Holocene pattern is weak because much of the data is dominated by local variations reflecting differential loading of the continental shelf by water during the Holocene transgression. The Holocene trend surface does not support geophysical modelling implying a southern latitudinal downwarping of the crust produced by the melting of the Antarctic ice sheet and the loading of the ocean crust with meltwater. However the spatial pattern of modern trends appears to contain a remnant Holocene signal fitting this isostatic model rather than the long term pattern of tectonic flexure since the last interglacial. Sea-level is presently rising at a rate of 1.75mm yr-1 in northern Australia compared to only 0.75mm yr-1 in Tasmania. These results imply that isostatic factors, as well as previously identified climatic variables, may be controlling present-day variations in the rate of change of sea-levels around the Australian continent.

Keywords

sea level, Australia, Holocene, Last interglacial

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details

This article was originally published as Bryant, EA, Last interglacial and Holocene trends in sea-level maxima around Australia: Implications for modern rates, Marine Geology, 108(2), 1992, 209-217. The original article is available here.

Last interglacial and Holocene trends in sea-level maxima around Australia: Implications for modern rates

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(Received December 23, 1991; revision accepted May 19, 1992)

ABSTRACT

Bryant, E., 1992. Last interglacial and Holocene trends in sea-level maxima around Australia: Implications for modern rates. *Mar. Geol.*, 108: 209–217.

This paper defines the spatial trend in sea level around Australia at 3 timescales, namely at the time of the maximum of the last interglacial around 125,000 yr B.P., during the Holocene maximum between 5000 and 6000 yr B.P. and over the last 20 years. Last interglacial elevations range from −2 m around the Great Barrier Reef to +32 m in northeast Tasmania. Trend surface analysis shows that over 77% of the noise in these sea-level elevations can be accounted for by a pattern evidencing tectonic uplift towards the southern edge of the continent. Assuming a eustatic sea level at this time of +4 to 6 m, most of the east coast of New South Wales and the west coast of Western Australia can be considered tectonically stable, while the southern edge of the continent has risen by at least 5 m and the north-northeast corner has downwarped by at least 2 m. The spatial pattern of the Holocene maximum tentatively supports the continuation of this tectonic deformation. Sea level at this time reached 1.6 and 2.4 m above present high tide limits around the northern and southeastern coastlines of Australia respectively. This Holocene pattern is weak because much of the data is dominated by local variations reflecting differential loading of the continental shelf by water during the Holocene transgression. The Holocene trend surface does not support geophysical modelling implying a southern latitudinal downwarping of the crust produced by the melting of the Antarctic ice sheet and the loading of the ocean crust with meltwater. However, the spatial pattern of modern trends appears to contain a remnant Holocene signal fitting this isostatic model rather than the long term pattern of tectonic flexure since the last interglacial. Sea level is presently rising at a rate of 1.75 mm yr^{-1} in northern Australia compared to only 0.75 mm yr^{-1} in Tasmania. These results imply that isostatic factors, as well as previously identified climatic variables, may be controlling present-day variations in the rate of change of sea levels around the Australian continent.

Introduction

Studies of sea level in Australia generally have been concerned with the identification of elevations over geological time, mainly during the last interglacial (Chappell, 1987; Murray-Wallace and Belperio, 1991) and through the Holocene (Thom et al., 1969; Gill and Hopley, 1972; Hopley, 1983), or with the causes of present rates of sea-level change (Church et al., 1986; Pariwono et al., 1986; Aubrey and Emery, 1986; Bryant, 1987; Bryant et al., 1988). The realization that the two may be interlinked has received scant attention. This has occurred because the emphasis has been placed on individual sites either in describing local sea-level history or in determining the reasons for present day, short term change. There has also been a tendency to generalize and view Australia at least in modern terms as tectonically stable. Only recently has it been recognized that the last interglacial maximum was not uniform around the continent (Murray-Wallace and Belperio, 1991). This non-uniformity has not been widely recognised for the Holocene transgression. The most quoted Holocene sea-level curve for Australia is that of Thom and Chappell (1975) latter modified by Thom and Roy (1983). Both approximations are partially based upon ^{14}C determinations from

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a part of the New South Wales coast which appears to be anomalous in terms of the height and timing of the Holocene maximum (Hopley, 1987; Bryant et al., 1992). Certainly the idea of a tectonic signature in modern rates of sea-level change in Australia is rarely considered (Bryant et al., 1988; Wallace, 1989).

Over the last 2 decades extensive dating of Holocene deposits using conventional ^{14}C techniques has given Australia one of the best spatial records of Holocene sea-level behaviour in the world (Hopley, 1983). In the past decade substantial effort has also been made in applying newer dating techniques to sea-level determinations around the Australian coastline at timescales beyond the limits of conventional ^{14}C dating. These techniques consist of improved uranium-series disequilibrium methods (Bryant et al., 1990), amino acid racemisation (Belperio et al., 1984; Murray-Wallace et al., 1991), electron spin resonance (Murray-Wallace and Goede, 1991) and thermoluminescence (Belperio et al., 1984; Bryant et al., 1990). Detailed descriptions of the techniques are beyond the scope of this paper, however, the references listed above provide substantial background information. Often, dates at many sites have been verified using 2 or more procedures or methods. As a result the elevation and timing of the last interglacial oxygen isotope substage 5e maximum has been well established around the continent (Murray-Wallace and Belperio, 1991).

These geological data bases and the present distribution of tide gauges permit trends in sea-level behaviour to be determined and explained around the continent at several timescales. The spatial aspect of such an approach has been used by Nakada and Lambeck (1989) in their attempt to model the ocean crust response around the Australian continent to glacial meltwater loading during the Holocene, and by Wallace (1989) who was concerned with detecting localized tectonic movement in the southwestern part of West Australia. The spatial trends of geological determined peaks in sea level also contain information on the overall tectonic deformation at the margins of the continent while the trends of present day rates of sea-level change contain remnant information about the Holocene response of the adjacent ocean to sea-level rise following the last glacial. In this paper, these trends across Australia are outlined at three timescales: the last interglacial maximum at 125,000 yr B.P., the Holocene maximum between 5000 and 6000 yr B.P. and over the last 20 years. The results will show that geological patterns of sea level at warmer temperatures are not the proper analogue for sea-level predictions around the Australia coastline under a greenhouse warmed climate. In addition, it will be shown that existing tide gauge records, besides being dominated by climatically induced sea-level changes, may contain a remnant isostatic signature that has not previously been identified.

Last interglacial sea-level trends

There has been debate within Australia about the maximum level of the last interglacial sea level (Chappell, 1987). The latest and best comprehensive review by Murray-Wallace and Belperio (1991) concludes that there is little evidence of a uniform 4–6 m elevation commonly cited in the world literature. Using 35 published ages determined for mainly in situ shell using a range of dating techniques they deduced that sea level peaked at the globally accepted age for oxygen isotope substage 5e at $125,000 \pm 10,000$ yr B.P. The most consistent elevation in this data set was at +2 m above present sea level; however, elevations varied from −2 m around the Great Barrier Reef to +32 m in northeast Tasmania (see Fig. 1 for location of place names). On the basis of these ages, they divided the continent into 16 zones which they believed could be differentiated from each other by regional differences in neotectonic deformation. Regions of relative upwarping included the coast south of Adelaide, the Coorong coastal plain and northern Tasmania. Relative subsidence had occurred in northern Australia. Bryant et al. (1988) also realized that Australia evidenced variation in neotectonic deformation but took a more conservative view in dividing the continental margins into only 4 distinct regions. They still suggested that northern Australia could be tectonically sinking in places.

Whether or not the Australian coastline can be divided into 4 or 16 segments reflecting local

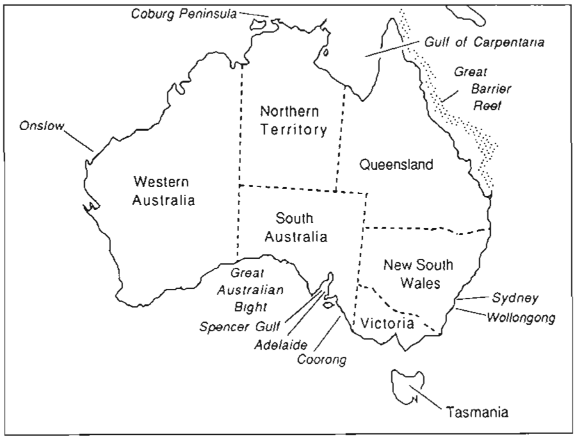

Fig. 1. Location map of Australia with place names mentioned in the text.

tectonism masks what may be a fundamental response of last interglacial sea level to movement of the Australian plate. This overlying trend in last interglacial sea levels was investigated using trend surface analysis. Trend surface analysis is a special case of linear multiple regression in which a dependent variable (in this case sea level) can be related to 2 independent variables which lie orthogonal to each other (Davis, 1973). In the classical sense, the independent variables are spatial and represent x- and y-coordinates on some mappable surface. In addition, trend surface analysis utilizes non-linear relationships based upon polynomial equations. Thus a planar, quadratic, cubic or even higher order surface can be fitted to the data. The technique is not always accurate because many published computer programs fail to minimize the rounding error generated using large powers. Modern algorithms now minimize this problem. The program published in Davis (1973) has been used but modified to reduce rounding errors.

Thirty-four sea-level elevations for the last interglacial were extracted from the publication of Murray-Wallace and Belperio (1991). These elevations were chosen to represent coverage around the Australian coastline and local variation. The data were augmented by a sea-level elevation of 0 m for the Coburg Peninsula, Northern Territory (Woodroffe et al., 1992) and an elevation of +2 m for Wollongong, New South Wales (Bryant et al., 1990). The dates for these heights were determined from iron crusts on rock platforms and reefs using uranium–thorium techniques. Each site in the data base was located on an equal area projection of Australia and its x- and y-coordinates digitized. All heights were related to present mean sea level.

Trend surface results for the quadratic surface are plotted in Fig. 2 and show the general tectonic response of the margins of the Australian continent since the last interglacial. Note that for presentation purposes, the pattern covers the continent. This is not meant to characterize any deformation that may be present over the interior of the Australian landmass. The second order surface was the most stable and accounts for 77.3% of the variance in last interglacial sea levels, a result that is statistically significant at the 0.05 level. Throughout the Tertiary, Australia has behaved as a plateau rifted along most its margins and affected by broad warping and a tendency for overall tilting depending upon the rate that it has drifted northwards (Jenkins, 1984). Figure 2 complements this pattern. The trend surface is one of tectonic warping increasing in elevation southwards and towards the margins of the plate. Ignoring local tectonic effects, a slight tilting of the Australian plate

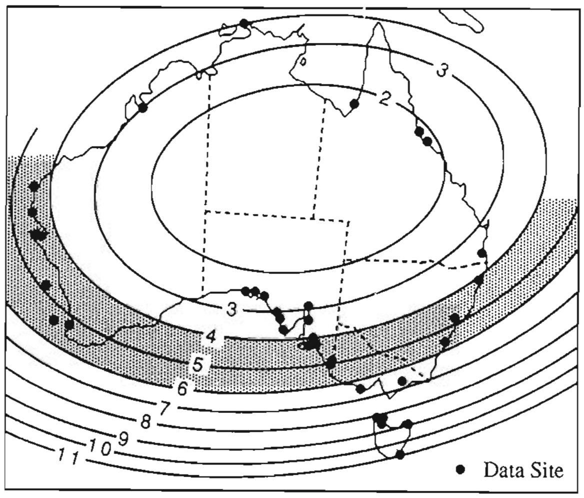

Fig. 2. Trend surface of last interglacial sea-level elevations. Values are in meters above mean sea level. Variance explained equals 77.3% which is significant at the 0.001 level. Note that for presentation purposes, the pattern covers the continent. This does not reflect any deformation that may be present over the interior of the Australian landmass.

towards the north-northeast is superimposed upon this pattern. Note that these patterns contradict the conclusions of Aubrey and Emery (1986) who have inferred incorrectly from modern sea-level records that the Australian plate was tilting upwards to the north. While the trend surface in Fig. 2 overestimates some of the elevations in northern Australia and underestimates some of those in Tasmania, the pattern is clearly one of continent-wide deformation. There is no need to invoke localized hot spot activity to account for the apparent anomalously higher Tasmanian elevations (Bowden and Colhoun, 1984). These high sea levels fit within a broader picture across the whole of the southern portion of the continent that probably reflects crustal underplating, not just for Tasmania (Bowden and Colhoun, 1984), but also for the whole of the Australian plate as it has drifted northward. Because Tasmania lies farther from the centre of the Australian plate than other parts of southern Australia, it has had greater upwarping and evidences higher sea-level deposits.

If the hypothesis that last interglacial eustatic sea levels were globally synchronous and higher than the present interglacial is correct, and this point is moot (Mörner, 1987), then the results in Fig. 2 can be adjusted for that elevation. The exact magnitude of the supra-elevation is questionable but generally ranges between 4 and 6 m above present mean sea level (Veeh, 1966; Mercer, 1978). Based upon mass volume calculations for the present West Antarctic icecap whose melting is presumed responsible for the last interglacial high sea level, this figure may be closer to 4.5 m (Budd, 1987). If the range in elevations is subtracted from Fig. 2, then less than half of the continental coastline can be considered tectonically stable. The regions of relative stability are shaded on Fig. 2 and cover the majority of the New South Wales coastline north of Wollongong, the South Australian coastline between Adelaide and western Victoria, and the West Australian coastline between Onslow and the outer Great Australian Bight. The New South Wales pattern reflects a tectonic stability that can be traced back through the Late Quaternary (Marshall and Thom, 1976; Bryant et al., 1990) and into the Tertiary (Young and McDougall, 1982). However, it is important to note that the Australia-wide pattern reflects an overall trend; significantly different local variations can exist for a number of reasons (Bryant et al., 1988; Murray-Wallace and Belperio, 1991). For instance, there is evidence of localized tectonic movement in southwest West Australia (Semeniuk and Searle, 1986; Murray-Wallace and Kimber, 1989), in the Spencer Gulf region (Hails et al., 1984; Belperio, 1985) and the Coorong of South Australia (Schwebel, 1984).

Assuming that the residual elevations after subtracting this 4–6 m value represent the deformation of the continental margins and that this deformation is constant over time, then maximum rates of uplift of 0.04–0.056 mm yr^{-1} have occurred in Tasmania while maximum rates of sinking of 0.016–0.032 mm yr^{-1} have occurred in the Gulf of Carpentaria and along the north Queensland coast. Since the Holocene transgression reached present sea levels approximately 7200 years ago, these rates would have generated maximum sea-level offsets around the Australian coastline amounting to 0.4 m of maximum uplift in the south and 0.23 m of maximum sinking in the north, a difference in height of 0.63 m. These changes would be difficult to detect stratigraphically given the fact that Holocene sea levels possibly fluctuated by 1–2 m (Chappell, 1987; Nakada and Lambeck, 1989; Bryant et al., 1992).

Holocene sea-level trends

To date much of the evidence in the literature for the trend in the Holocene sea-level supra-elevation runs counter to the trend in Fig. 2. Nakada and Lambeck (1989) used a model describing the Earth's non-elastic response to surface loading to describe the sea-level response around the Australian coastline at the peak of the Holocene transgression between 5000 and 6000 yr B.P. This model included lithospheric thickness, upper mantle viscosity and lower mantle viscosity below 670 km depth. There was a tendency for Holocene sea level to increase northward around Australia with increasing distance from the Antarctic continent. These trends do not reflect tectonic behaviour of the continent but rather the deformation of the crust produced by the melting of the Antarctic ice

sheet in particular, and the loading of the ocean crust with meltwater. Significant local variations occurred. For instance, the model predicted that the continental shelf was quite sensitive to upper mantle viscosity and tilted as it was loaded with water. This tilting decreased in amplitude with distance seaward and tended to produce a regional variation in the time of the Holocene transgression peak. Southernmost sites evidenced a highstand first, while island sites lagged as much as 2000 years behind. In addition, small coastal indentations gave rise to significant regional variations because of the differential effects of loading away from the continental shelf edge. For instance, relative sea levels reached elevations of +2.5 m between 1700 and 6000 yr B.P. at the head of Spencer Gulf (Belperio et al., 1984), a fact that Nakada and Lambeck (1989) attribute to these isostatic variations rather than to any tectonic factor.

The trend for increasing sea-level maxima northwards was considered to be a notable feature of the modelling; however, the authors in this and subsequent articles have not adequately correlated this result with the field evidence (Lambeck and Nakada, 1990; Lambeck, 1990). An extensive data base for Holocene sea-level maxima exists in Australia based predominantly on the dating of in situ shell and supplemented by stratigraphic evidence. Using the limited data published by Nagata and Lambeck (1989) and the comprehensive results published in Hopley (1983), augmented by field observations based upon thermoluminescence dating of beach sands, and uranium–thorium dating of iron crusts on rock platforms and reefs (Bryant et al., 1992; Woodroffe et al., 1992), heights of the Holocene sea-level maxima above present high tide limits were determined for 42 locations around the Australian margin for the period 5000–6000 yr B.P. These observations were then subjected to trend surface analysis.

The results of this analysis are informative. The most significant surface was obtained for the planar surface although the degree of explanation is 9.4% which is statistically significant at only the 0.14 level. The trend surface is presented here (Fig. 3) not as an authoritative map of Holocene sea levels in Australia, but as a first approximation to which future results can be referenced. The trend suggests that Holocene sea levels peaked higher towards the southeastern part of the continent. The trend in this supra-elevation ranges from a low of 1.6 m in northern Australia, to a value of 2.4 m in the southeast corner of the continent, a difference in magnitude of 0.8 m. Surprisingly this latitudinal difference corresponds to the 0.63 m deviation determined above for continent-wide tectonic deformation over the last 7200 years based upon the height of last interglacial sea levels. At the broad scale, the field evidence does not support the modelling by Nagata and Lambeck (1989) for the crustal response of Holocene sea level in the Australian region. At the local scale, the trend model even appears to explain high Holocene sea levels in the Spencer Gulf area, attributed by Belperio et al. (1984) to local tectonic movement and by Nakada and Lambeck (1989) to local isostatic flexure. A remnant tectonic signature, active since at least the last interglacial, appears to describe adequately the broader spatial distribution of the Holocene sea-level maximum in the Australian region.

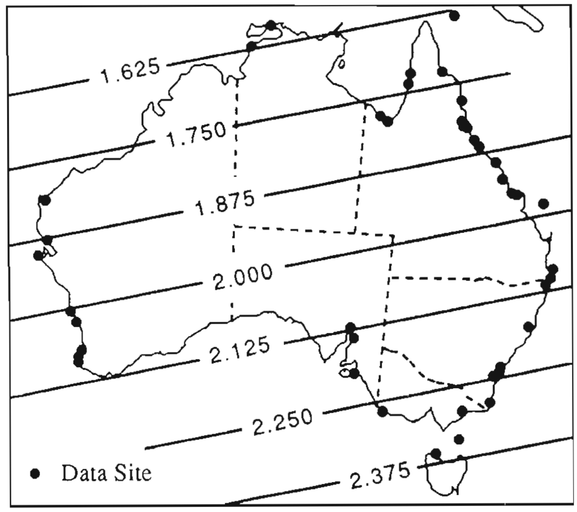

Fig. 3. Trend surface of Holocene peak sea-level elevations 5000–6000 yr B.P. Values are in meters above present high tide limits. Variance explained equals 9.4% which is significant at the 0.14 level. Note that for presentation purposes, the pattern covers the continent. This does not reflect any deformation that may be present over the interior of the Australian landmass.

Present sea-level trends

There has been considerable debate about the nature of existing sea-level trends within Australia (Church et al., 1986; Pariwono et al., 1986; Aubrey and Emery, 1986; Bryant, 1987; Bryant et al., 1988). One of the most glaring inconsistencies was Aubrey and Emery's (1986) premise that present sea levels were related to continent-wide tectonic factors. The continent in this framework was supposed to be tilting southwards. Bryant et al. (1988) not only showed this to be incorrect, a fact supported by Fig. 2, but also demonstrated that local factors were more important. These factors included localized tectonics, continental shelf loading, climatic variation and oceanographic currents and shelf waves. Australian tide gauges overall do not support a eustatic rise of sea level because the continent is not uniformly stable tectonically. However, it has been tempting to consider the Sydney sea-level change of 0.56 mm yr^{-1} as reflecting a global eustatic rate because it occupies a zone in Fig. 2 of minimum deformation since the last interglacial. This premise is questionable because no one has realized that a further complicating factor may exist for Australian tide gauges, namely the continuation of the oceanic crustal adjustment to Holocene meltwater loading following the demise of the last glacial as outlined by Nakada and Lambeck (1989). If this were the case then the Sydney tide gauge record, as with most other Australian records, may be showing trends that are also a remnant part of the isostatic Holocene signature.

It is possible to assess the trend of modern sea-level rise for the Australian continent. Wallace (1989) has attempted to do this using annual trends for 30 tide gauge stations supplied by the National Tidal Laboratory at Flinders University. Most of these stations consist of 20 years of record commencing in 1966. The gauges have been assessed for accuracy and reliability and meet criteria established by the Bidston Laboratory in the United Kingdom. Wallace culled dubious rates of sea-level rise from his data set and used a multiple regression model to assess the trend of sea level over the continent. However, in doing so he neglected the joint contribution of latitudinal and longitudinal variations. The National Tidal Laboratory data set was reanalysed using trend surface analysis to include this latter term. The results are presented in Fig. 4.

Present day trends in sea level are spatially much more variable than the elevations of last interglacial sea level. Only the planar trend surface is statistically significant, at the 0.05 level accounting for 18.3% of the variance in present-day sea-level trends. This is slightly less than the degree of explanation (19.5%) achieved by Wallace (1989) and significantly less than the degree of explanation reached for last interglacial sea-level elevations (Fig. 2). The lower degree of explanation reinforces earlier views that present day sea-level changes in Australia are affected by a number of factors most of which are probably climatically induced and which may not show coherence over long distances, at least not across a continent the size of Australia (Bryant et al., 1988). The trend largely consists of an increased rate of sea-level rise northwards with a weak north-northeast inclination. The northward trend is the inverse of sea-level elevations reached during the last interglacial (Fig. 2) and inferred for the Holocene (Fig. 3), and thus must be assumed not to be a reflection of this longer term tectonic effect. The direction of modern day rates of sea-level change are very consistent with those hypoth-

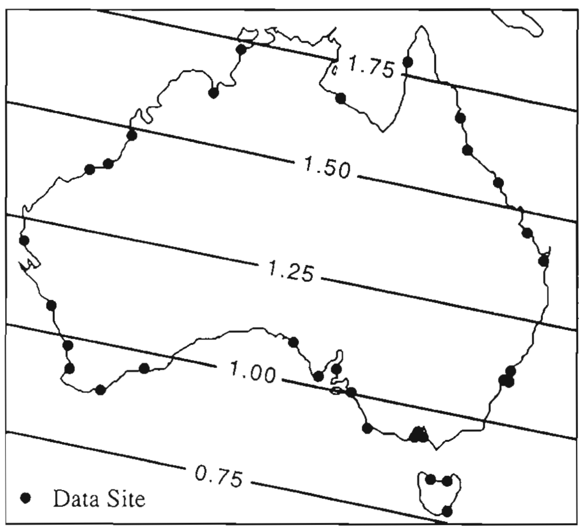

Fig. 4. Trend surface of modern rates of sea-level change. Values are in millimeters per year. Variance explained equals 18.3% which is significant at the 0.05 level.

esized by Nakada and Lambeck (1989) reflecting the continued impact of crustal flexure as a response to icesheet melting of the Antarctic and ocean crust loading. This model has sea level increasing northwards around the continent. The modern record thus supports Nakada and Lambeck's model of crustal deformation better than the presently compiled geological record for the Holocene as described above (Fig. 3).

A note of caution should made regarding this interpretation. Climatic factors cannot be ruled out as the cause of modern trends in sea level in the Australian region (Bryant et al., 1988). The trend in Fig. 4 parallels the recent trend for the steric sea-level gradient between the equatorial west Pacific and the Antarctic (Levitus, 1982). This gradient is maintained by wind forcing and is most likely produced by enhanced easterly trade winds. Similarly the modern trend could just as easily be generated by a globally warmer ocean in Sverdrup balance with the wind field as modelled by Godfrey (1989). While it may be tempting to see this as evidence of Greenhouse warming, field data to substantiate such a projection are still inconclusive.

Conclusions

This paper has examined the pattern of sea levels around the margins of Australia at 3 timescales: the maximum of the last interglacial around 125,000 yr B.P., the Holocene maximum between 5000 and 6000 yr B.P. and for the last 20 years. The last interglacial is distant enough in time that rates of deformation around the Australian margins are evident in sea-level elevations relative to modern datum. Trend surface analysis has shown that a highly significant spatial pattern exists with tectonic warping of the margins of the continent. This warping consists of substantial uplift towards the southern edge of the continent, by at least 5 m, and slight downwarping to the north-northeast, by at least 2 m. If eustatic sea levels during the last interglacial were between 4 and 6 m higher than present, then most of the east coast of New South Wales and the west coast of Western Australia are tectonically stable. The trend for New South Wales is a continuation of one established throughout the mid to late Tertiary.

The spatial pattern of the Holocene maximum around Australia tentatively supports the continuation of the tectonic processes responsible for sea-level variations since the last interglacial. There is a weak tendency again for sea levels to increase towards Tasmania concomitantly with the last interglacial pattern. If it can be assumed as a first approximation that tectonic deformation based upon the trend surface of last interglacial sea levels was constant over time, then the magnitude of this deformation in the last 7200 years amounts to 0.4 m in Tasmania and -0.23 m in northern Australia. The actual supra-elevation based upon the trend surface of Holocene levels ranges from a low of 1.6 m in northern Australia, to a high of 2.4 m in Tasmania. The difference in the magnitude of sea-level displacement latitudinally across the Australian continent is similar in both approaches. The Holocene pattern is only weakly defined because Holocene sea levels are dominated by large local variations which probably reflect regional loading of the shelf by water during the Holocene transgression. The Holocene data set does not support geophysical modelling implying a southern latitudinal downwarping of the crust produced by the melting of the Antarctic ice sheet in particular, and the loading of the ocean crust with meltwater. This is not to say that this deformation did not occur. The modern trends, rather than supporting the long term pattern of tectonic flexure since the last interglacial, support the geophysical Holocene modelling. Sea level is rising faster at a the rate of 1.75 mm yr^{-1} in northern Australia compared to only 0.75 mm yr^{-1} in Tasmania. Thus there may be a remnant isostatic Holocene signal present in the rate of modern sea-level change in the Australian region.

These results have implications for the determination of future rates of sea-level change around Australia. Firstly, the last interglacial maximum is not an analogue of future sea-level elevations in the Australian region if sea levels globally rise by several meters in the next few centuries. It would appear that the differences in the elevation of last interglacial sea levels around Australia are tectonically, rather than climatically dominated. Secondly, a eustatic change in sea level cannot be determined from Australian tide gauges. One

reason for this failure is the possibility of continuing isostatic flexure of the continent due to Holocene responses of the continental shelf to deglaciation. More effort in defining the levels of the Holocene maximum around Australia should make it possible to determine the ongoing rate of of this remnant flexure at any tide gauge. Thirdly, the pattern of Holocene maximum sea-level elevations and recent trends reinforces the view that sea levels around Australia have, and will continue to show, large local variation. While coherence is detectable amongst tide gauges around long sections of the continent, significant variations exist because of climatic and tectonic influences. Finally, this study does not detract from the fact that climatic variations are the dominate control on the rates of present-day change at most tide gauges around Australia. Indeed, much of the spatial pattern of recent sea-level trends parallels that resulting from climatic change on a hemispheric scale.

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