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Abstract

The recent detailed analyses by Aubrey and Emery (1986) of Australian sea level trends continues their efforts to define tectonic and climatic factors worldwide that dominate long- and short-term fluctuations respectively in sea level records. These factors have included sediment and water loading on the adjacent shelf, the tectonic behaviour of plates, fluctuations in the Southern Oscillation, behaviour of currents impinging on the shelf, and river runoff. We do not object to these efforts; however we are disturbed by misrepresentations in their recent paper on Australian sea levels regarding (1) the interpretation of the nature of sea-level records, (2) the use of tectonic explanations to account for low-frequency sea level trends and (3) the somewhat incomplete and sometimes inaccurate consideration of the effects of climatic variables upon sea level fluctuations and trends.

Keywords

sea level change, Australia, tide gauges

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AUSTRALIA—AN UNSTABLE PLATFORM FOR TIDE-GAUGE MEASUREMENTS OF CHANGING SEA LEVELS: A DISCUSSION[1]

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INTRODUCTION

The recent detailed analyses by Aubrey and Emery (1986) of Australian sea level trends continues their efforts to define tectonic and climatic factors worldwide that dominate long- and short-term fluctuations respectively in sea level records. These factors have included sediment and water loading on the adjacent shelf, the tectonic behavior of plates, fluctuations in the Southern Oscillation, behavior of currents impinging on the shelf, and river runoff. We do not object to these efforts; however we are disturbed by misrepresentations in their recent paper on Australian sea levels regarding (1) the interpretation of the nature of sea level records, (2) the use of tectonic explanations to account for low-frequency sea level trends, and (3) the somewhat incomplete and sometimes inaccurate consideration of the effects of climatic variables upon sea level fluctuations and trends.

THE NATURE OF AUSTRALIAN SEA LEVEL RECORDS

Geophysical time series such as sea level curves are characterized by at least five features that affect the calculation of trend lines. First, if the signal-to-noise ratio is low, statistically significant trends may be meaningless in characterizing records. Aubrey and Emery (1986) attempt to overcome the problem of noice by using eigenanalysis of tidal records selected around the Australian continent. In doing so they mask the variable nature of some records and define trends that are artifacts of short record lengths. This is clearly the case for the Darwin and Cairns sea level records (fig. 3, p. 705), which unfortunately represent their only evidence for falling sea levels within Australia.

Second, the amplitude of fluctuations in sea level time series can change over time. These shifts in record variance often appear in eigenanalysis at eigenfunctions close to the noise level of the data; however their timing is crucial in accounting for sea level behavior. For instance, the variance in the Fort Denison, Sydney sea level record increased after 1948 concomitantly with more erratic behavior in rainfall and sea surface temperature (Bryant 1988*a*) and a more variable climate generally after 1948 (Bryant 1985). This change manifests itself in most long term Australian sea level records. It is depicted but not explained by Aubrey and Emery in their plot of the second eigenfunction (1986, fig. 5, p. 706).

Third, time series may not vary smoothly but instead show random, step-functional changes in the mean of the record over relatively short periods of time. The increase in sea level at Sydney and Newcastle around 1948 is step-functional and coincident with the climatic shift mentioned above. The timing of this step also accounts for the large difference between rates of sea level rise between Fort Denison and Camp Cove 6 km apart within Sydney Harbor. The Camp Cove record depicts only the higher sea levels after 1948 while the Fort Denison record includes an earlier phase of lower sea levels and thus has the higher rate of increase over time. In actual fact both records parallel each other where they overlap after 1948.

Fourth, time series may exhibit periodicity or substantial long-term serial or autocorrelation. This can lower confidence levels, generate false trends if records do not begin and end at the same point in these oscillations, or produce erroneous trends that are not representative of the true behavior of the time series even if they are long-term. Aubrey and Emery (1986) indirectly consider this limitation, but they are left mapping only 13 out of

25 stations in their eigenanalysis in figure 6 (p. 707). This leaves too few, poorly spaced stations to permit varying continent wide sea level patterns to be explained.

Finally, geophysical time series often differ spatially in character over very short distances even after eigenanalysis has been performed. For example, sea levels within Newcastle harbor increased at rates of 3.0–4.7 mm/yr, while within Sydney harbor 200 km away they increased by only 0.4–1.4 mm/yr. The disparity is most likely due to the differing effect of runoff following enhanced rainfall after 1948. Within Newcastle harbor runoff is significant because of the large but variable through flow of the Hunter River, whereas within Sydney harbor runoff is less significant because this harbor is devoid of any large river. Additionally, differences could relate to variations in the amplitude of continental shelf waves set up by wind stress and the mean longshore current across the entire width of the continental shelf (Hamon et al. 1975). Variations within Sydney harbor (and probably Newcastle and Port Adelaide), reflect site specific responses to wind and shelf waves, atmospheric pressure, and wind stress (Thompson 1983). To ignore this intraharbor variability, or to ascribe high-frequency fluctuations solely to one factor such as the Southern Oscillation without examining other mechanisms, incompletely describes Australian sea level behavior.

TECTONIC EFFECTS ON AUSTRALIAN SEA LEVELS

More important, Aubrey and Emery's (1986) tectonic explanations for low-frequency sea level responses in Australia ignore the volume of literature on Quaternary Australian sea levels that directly contradicts their conclusions. Their claims, that sea level over the past 20–90 yrs has been rising on average in the southern part of the continent by 1.4 mm yr^{-1} and falling in the north by 0.5 mm yr^{-1} and that such trends can be attributed to subsidence in Cainozoic basins and southward tilting of the Australian plate, are oversimplistic and unsupported. Tectonic emergence of the northern coast of Australia during the Cainozoic is unfounded, while shoreline emergence during the Holocene can be interpreted simply using a hydroisostatic model (Chappell et al. 1982). Basin subsidence in southern Australia inadequately accounts for a tiny fraction (0.02 mm yr^{-1}) of observed changes as admitted by Aubrey and Emery themselves (1986, p. 708) and shown by Roy and Thom (1981) for the youngest southeast margin of the continent (0.25 mm yr^{-1}). What is most striking is the failure of Aubrey and Emery (1986, p. 707) to appreciate that across southern Australia, Quaternary marine deposits (including the Holocene in some cases) within Cainozoic basins, such as the Gippsland, Oxley, Murray, Eucla, and Perth basins, are now elevated above present sea level (see Jenkin, 1984, for a synthesis of the data). Thus to say that "overall submergence is supported by the widespread distribution of basins along the entire margin of Australia excepting the east coast" (Aubrey and Emery 1986, p. 707) is in error as far as the history of Australian Quaternary shorelines is concerned.

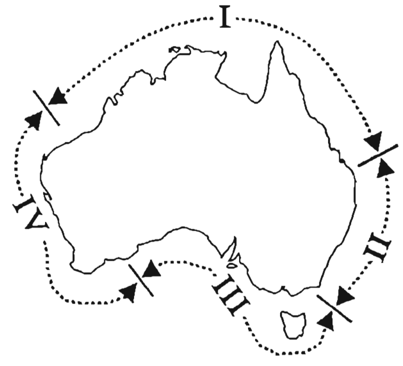

FIG. 1.—Map of Australia showing general limits of coastal and continental margin regions (I–IV) discussed in text.

Sufficient radiometric and stratigraphic data (Hopley 1983; Thom 1984) now exist for four separate regions of the Australian continent (fig. 1) on the age and elevation of two late Quaternary marine reference points: (1) the Last Interglacial high stand (stage 5e at ca. 125 ka), which was about 5 m above present sea level, and (2) the culmination of the Postglacial Marine Transgression which reached present sea level about 6500 yrs B.P. These data support the contention of Thom and Roy (1985) that Australia is a relatively stable continent and that extrapolation of tide gauge records into the geologic record as envisaged by Aubrey and Emery (1986) is untenable.

First, for Region 1 in northern Australia

(Great Barrier Reef to Dampier), Last Interglacial shorelines are either at or below present sea level. Throughout the Great Barrier Reef Province, Pleistocene limestone has been encountered at elevations no higher than 4 m below present sea level (Thom et al. 1978; Davies and Hopley 1983). No higher Quaternary marine deposits older than Last Interglacial and no Holocene deposits more than 3 m above present sea level have been reported from this region. Mid-Holocene higher sea levels at least can be attributed to hydroisostatic effects (Chappell et al. 1982). Dated sequences include chenier plains (Rhodes 1982; Chappell et al. 1983; Chappell and Grindrod 1984), mangrove sequences in the south Alligator River (Woodroffe et al. 1986), and microatolls and other coral reef relative sea level indicators (Hopley 1983; Chappell et al. 1983). Woodroffe et al. (1986) even conclude that the van Diemen Gulf area may be tectonically sinking.

Second, in southeastern Australia (Region II on fig. 1), the oldest, Last Interglacial marine shorelines lie 3–6 m above present sea level (Marshall and Thom 1976). Accurate positioning of Holocene marine and estuarine deposits are hampered by a lack of precise relative sea level indicators such as mangrove stumps and salt marsh peats in estuaries and by high energy storm waves and a tidal range up to 2 m on the open coast. However, the Holocene stillstand has occurred at present sea level (± 1 m) over the last ca. 6500 yrs. Isolated areas with more precise data include reef corals at 1 m above present sea level in southern Queensland dating 4000–5000 yrs B.P. in age (Flood 1983) and intertidal estuarine shells in southern New South Wales that show no change in relative sea levels during the past 3000 yrs (Donner and Jungner 1981).

Third, in southern Australia (Region III in fig. 1), contrary to Aubrey and Emery's supposition, there is evidence of significant tectonic uplift in a number of areas. A "staircase" of interglacial marine deposits occurs in the eastern part of South Australia extending back at least 700,000 yrs (Schwebel 1984; Cook et al. 1977). Northeastern Tasmania evidences a sequence of Quaternary shorelines with inner segments of the Last Interglacial elevated about 20 m above present sea level (Bowden and Colhoun 1984). During the Holocene, there is abundant evidence for a relative stillstand at present sea level over the past 6500 yrs with some indicators of a +2 m high stand in the mid-Holocene (Hails et al. 1983). There is no clear evidence that tectonism has modified the elevation of Holocene shorelines in Tasmania, but in Spencer Gulf in South Australia it may be a factor (Hails et al. 1983).

Finally, in Western Australia (Region IV in fig. 1), Last Interglacial shorelines range from +10 m at Northwest Cape to +4 m near Perth. In some areas older Quaternary marine deposits are preserved at higher levels (van de Graaff et al. 1976). The general trend is for a slightly higher sea level (+1 to +3 m) between 5500 and 6000 yrs B.P. followed by a progressive decline to present sea level. Data sets include prograded beachridge sequences, intertidal and supratidal shell deposits, and mangrove deposits (Brown 1983). Local tectonism may have modified the primary disposition of these features in some areas (see Semeniuk and Searle 1986).

Clearly the above evidence from the late Quaternary does not accord with extrapolated trends defined by Aubrey and Emery (1986) using recent Australian tide gauge records. In fact, where there is evidence for localized earth movements (subsidence in northern Australian and uplift in Southern Australia), documented displacements are in the reverse direction. The distorted picture raised by Aubrey and Emery (1986) now makes it imperative that specific information on Quaternary shoreline displacement be included in any model of crustal and/or ocean surface movements in Australia.

METEOROLOGICAL AND OCEANOGRAPHIC INFLUENCES UPON AUSTRALIAN SEA LEVEL

Aubrey and Emery (1986) also fail to realize that a wide range of meteorological and oceanographic variables can affect sea levels and that changes in these variables over time can account for some of their defined trends. We firmly support Aubrey and Emery's belief that the Southern Oscillation is one of the prime factors controlling sea levels throughout the Pacific region (see Pariwono et al. 1986 for Australia). However, they are incorrect in asserting that at times of ENSO events "there is competition between lowered sea levels due to higher atmospheric pressure

TABLE 1

SEA LEVEL CORRELATIONS AND EIGENANALYSIS RESULTS

	A	B	
Variable	Correlation Coefficients	1st eigenfunction	2nd eigenfunction
Sea level	. . .	.24 (.18)	−.55 (−.58)
Storm	.38[a] (0.22)[b]	.33 (.30)	−.56 (−.30)
SO	.16[c] (0.23)[b]	.20 (.28)	−.05 (−.28)
SST	.14 (0.13)	.52 (.53)	.32 (.25)
Rainfall	.10 (−0.03)	.48 (.44)	−.11 (.00)
Hadley position	.00 (−0.10)	.54 (.55)	.35 (.37)
Air pressure	.12 (−0.36)[c]	−.05 (−.12)	−.38 (.54)
	eigenvalue	2.14 (1.95)	1.35 (1.35)
	% of trace	30.64 (28.03)	20.15 (22.31)

NOTE.—A. Cross correlations between quarterly sea-level and (1) accumulative storm wave height, (2) Troup's Southern Oscillation (SO) Index, (3) sea surface temperature (SST), (4) regional rainfall, (5) latitude of center of Hadley Cell along the east coast, and (6) atmospheric pressure at Sydney. Seasonally detrended values in brackets. B. Eigenanalysis results for the above data. Only component loadings for the first two eigenfunctions are above the noise level of the data. Seasonally detrended values in brackets.

[a] Significant 0.01 level.

[b] Significant 0.05 level.

[c] Significant 0.10 level.

coinciding with lower water temperatures, and raised sea levels due to steric effects related to freshwater discharge" (Aubrey and Emery 1986, p. 710). ENSO events which peak around Christmas are directly linked to drought conditions and low or non-existent freshwater discharge at this time in eastern Australia. It is only when an ENSO event abates in March of the following year that rainfall in eastern Australia returns to normal and begins to increase above average.

The Southern Oscillation, however, is not the only climatic variable affecting east Australian sea levels. Table 1 summarizes statistically the correlations (corrected for serial correlation) between Sydney sea level measured at 3 monthly intervals between 1943–1980 at Fort Denison and (1) accumulative, hindcasted storm wave heights off the Sydney coastline, (2) Troup's Southern Oscillation Index, (3) sea surface temperature (SST) measured at 34°05′S, 151°15′E, (4) regional rainfall averaged for Sydney and Helensburgh approximately 30 km to the south, (5) the latitude of the center of the Hadley Cell over the east Australian coastline, and (6) atmospheric pressure at Sydney. The definition and measurement of these terms are reported elsewhere (Bryant 1985, 1988*a*, 1988*b*). On a seasonal basis, sea level at Sydney is linked predominantly to accumulative storm wave heights immediately offshore (r = 0.38). When seasonality is removed from the data, sea level correlates most strongly with air pressure (r = −0.36), followed by strong relationships with the Southern Oscillation and accumulative storm wave heights (r = 0.23 and 0.22 respectively).

The interrelated behavior of all six variables, including sea level, was assessed over the period 1943–1980 using normalized eigenanalysis (table 1). Seasonality makes little difference to the overall results. The 1st and 2nd eigenfunctions together account for 50% of the data variance above noise level. The 1st eigenfunction represents the general climatic regime at Sydney and is weighted more toward Hadley Cell position, SST, and regional rainfall than it is toward sea level, storm waves, and the Southern Oscillation index. This eigenfunction suggests that as the Hadley Cell shifts poleward and/or Walker circulation strengthens concomitantly with increased SST, storm cyclogenesis and rainfall are enhanced, and ultimately Sydney sea level rises. This scenario also determines the timing of beach erosion along the Central and South coasts of New South Wales (Thom 1978; Bryant 1988*a*, 1988*b*). The 2d eigenfunction represents a fair weather state conducive to lower sea levels and associated with blocking by aseasonally strong, high pressure cells over the Tasman Sea.

Subtle change has been occurring to Australian climate; however, this change is not necessarily one of magnitude because the climatic variables in table 1 are trendless since 1943. What has altered is climatic variability. For example, storms have become more intense and droughts more severe with the intervening wet periods characterized by record breaking rainfalls. Furthermore this change in variability has not been spatially constant. For example, falls in Australian sea level during recent ENSO events have been larger over the tropical Pacific than along temperate parts of the eastern coastline. Additionally the strength of southeast trades between 1974–1981 has decreased, resulting in falling sea level at many western Pacific tide gauges in the tropics (Inoue and O'Brien 1987). The decreasing trends in sea level derived by Aubrey and Emery (1986) for Darwin and Cairns are not tectonically induced, but are reflections of more frequent ENSO events and decreasing trade winds in recent years.

In conclusion, we cannot accept Aubrey and Emery's (1986) explanations for sea level trends on the Australian continent. Well documented and accessible literature indicates that there is no tectonic evidence for the margins of the Australian continent rising in the north and falling in the south. In fact the opposite is true. Short-term sea level trends and fluctuations in the Australian region are not affected substantially at present by tectonics but by a myriad of interlinked meteorological and oceanographic factors including the Southern Oscillation, rainfall regimes, storm wave climatology, sea surface temperature, and Hadley Cell positioning. Explanations of spatial trends in sea level around the Australian continent must consider spatial changes in the nature of these climatic variables, and over the long term agree with the Quaternary record.

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