SEA LEVEL CHANGE AND GREENHOUSE: IMPLICATIONS FOR WETLANDS

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INTRODUCTION

In 1985, the Conference on Greenhouse Warming held at Villach, Austria, predicted a rise in sea level by 2030 AD of between 0.2 and 1.4 m caused by melting of ice-caps (including mountain glaciers) and thermal expansion of the oceans (World Meteorological Organization 1986). Recent research, however, suggests that thermal expansion of water in the upper 100-200 m of the oceans is the most likely major cause of future sea level rise. Predictions about the extent of this rise have been revised downward because it is now realized that warming of air around the Antarctic ice-cap will lead to increased snowfall, thus counteracting the effect of thermal expansion. What has not been widely recognized is the fact that sea level behaviour from year to year and over the long term, especially in Australia, is climatically controlled, with complex feedback mechanisms operating on regional scales (Bryant 1988a, Bryant *et al.* 1988). The short term variability in sea level behaviour may be 1-2 orders of magnitude greater than the average trends defined from many sea level records.

In this paper the nature and variability of sea level changes within Australia will be discussed first. Secondly, the impact of this variability upon Greenhouse predictions of sea level rise and some more current predictions for sea level elevations in the next 40 years will be presented. Thirdly, the impact of these sea level changes upon mangrove and saltmarsh wetlands will be assessed. Finally, planning options necessary to minimize the effect of rising sea level upon wetlands will be reviewed.

AUSTRALIAN SEA LEVEL TRENDS

Description of the Trends

The current world rate of sea level rise is between 1.0-1.5 mm yr^{-1} (Barnett 1983, Gornitz & Lebedeff 1987). Sea level trends for Australia are shown in Figure 1 and on average agree with this world rate. The Australian trends were calculated using published records compiled by the Permanent Service for Mean Sea Level (Aubrey & Emery 1986) and unpublished data on rates between 1966 and 1986 from the Tidal Laboratory, Flinders University. Rates of sea level rise appear to be higher towards the south of the continent. The highest rates are in South Australia around Spencers Gulf, and in Western Australia around Carnarvon and Wyndham. Slight falls in sea level are shown in the tropics, mainly along the Queensland coast. These falls were more prominent in the 1970s than at any other time in the data set. While in the short term there is good agreement with the global pattern, longer term rates within Australia may not reflect this situation. For instance, while the Sydney record shows a rise of almost 1.7 mm yr^{-1} over the past forty years, the long term rate since 1886 is only 0.54 mm yr^{-1}. The reasons for this variation will be discussed below. Figure 1 thus should be considered representative of changes in Australian sea level since 1960. It is not representative of records extending back into the 1800s nor should any attempt be made to interpret any acceleration of sea level rise due to Greenhouse warming. As most of Australia is a stable landmass tectonically, most of the variation and trends in Australian sea level can be related to regional climatic factors. It should be realized that over longer time periods, significant tectonic spatial variations in sea level rates have been noted, for example during the last several thousand years over distances of a few hundred kilometres along the South Australian and Western Australian coastlines (Belperio 1989, Semeniuk & Searle 1986).

Nature of the Trends

Figure 2 plots the longest of the Australian records, mean annual sea level for Fort Denison, Sydney, between 1886-1988. Over this period sea level has risen at a rate of 0.54 mm yr^{-1}, lower than the world rate of 1.0-1.5 mm yr^{-1} (Barnett 1983). While the Sydney rate has been as high as 2.7 mm yr^{-1} since 1948, the trend during the 1980s does not show any significant increase. The Sydney record (also see Newcastle Harbour, next page) characterizes much of the east coast of Australia (Aubrey & Emery 1986, Bryant *et al.* 1988). Hamon *et al.* (1975) previously identified this point, observing a strong link in sea level at most stations along the east coast with a strong dependence upon regional atmospheric pressure. Subsequently, Pariwono *et al.* (1986) found that Australian sea levels, continent wide, are strongly controlled by the Southern Oscillation, while Church and Freeland (1987) found strong similarities over a six month period in sea level behaviour between Esperance, WA, and Port Stephens, NSW, that related to the movement of coastal trapped shelf waves anti-clockwise around the coastline at about 10.4 m s^{-1}, in association with the eastward passage of weather

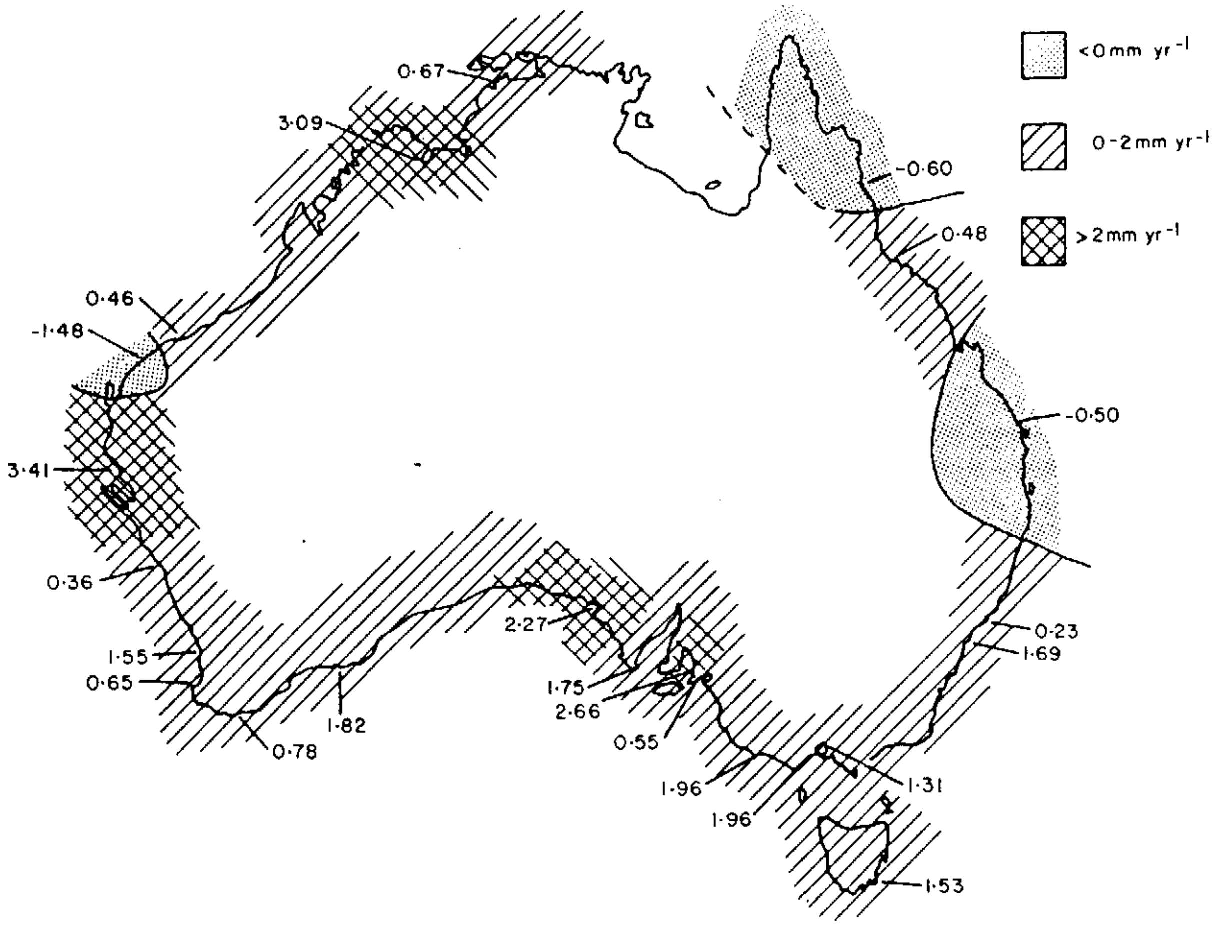

Figure 1 Sea level trends in Australia, mainly for the period 1960-1986.

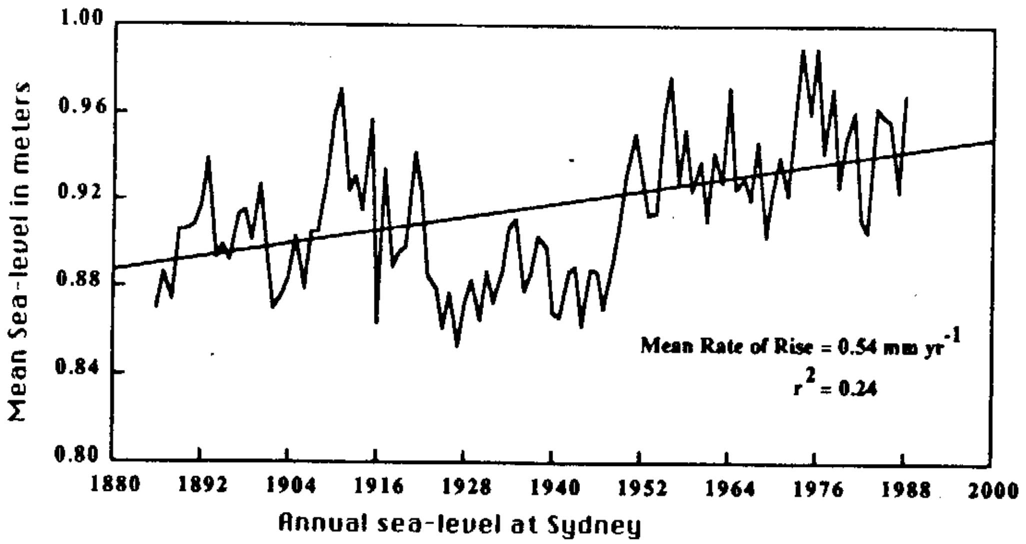

Figure 2 Annual sea levels at Sydney, 1886-1988.

systems. Shelf waves in the Australian region typically have a periodicity of one to seven days and amplitudes exceeding 0.5 m (Provis & Radok 1979). Church and Freeland (1987) and Huyer *et al.* (1988) also found in detailed studies along the south-east coast between Cape Howe and Newcastle that winds, coastal currents on the inshore shelf and sea level can be strongly interrelated at the seasonal level. Bryant *et al.* (1988) also found that as rainfall increases concomitantly with storm waves, sea level at both Newcastle and Sydney rises. However, if rainfall occurs when Hadley cells are more poleward, a condition that dominated the first six months of 1989, then sea level tends to fall.

Degree of Sea Level Variability

Local climatically induced variations in sea level do exist, sometimes over very short distances. For example, measured sea levels over the past 30 years within Newcastle Harbour have increased at rates of 3.0-4.7 mm yr^{-1}, while within Sydney Harbour, ~200 km away, they have increased by only 0.4-1.4 mm yr^{-1} (Aubrey & Emery, 1986). This regional disparity is most likely due to the differing effect of runoff following enhanced rainfall and catchment modifications after 1948. Newcastle Harbour is affected by the variable flow of the Hunter River, whereas Sydney Harbour is devoid of any large river inflow. Variations also exist within single harbours and probably reflect site specific responses to wind and shelf waves, atmospheric pressure and wind stress (Thompson 1983). The degree of sea level variability around Australia can be illustrated at both long and short time scales. The longer time scale is shown in Figure 3, which maps the maximum rate of sea level change from Australian tide gauges over timespans of 15 or more years. Positive and negative rates are presented in brackets for three stations, Newcastle, Fort Denison and Williamstown, Victoria. Figure 3 indicates that there are sharp changes in sea level trends at the decadal level in most Australian tide gauge records. Rates in the south-east corner of Australia span a range of more than 10 mm yr^{-1}, and can change sign and magnitude dramatically.

At the shorter time scale, sea level variability can be shown using SEASAT altimeter measurements for the period July-October 1978 (Marsh *et al.* 1986). This record is fortuitous because the south-east corner of the continent at this time was experiencing one of the stormiest periods measured for the past century (Blain *et al.* 1985). The altimeter readings, accurate to within 30-50 mm, are plotted in Figure 4 and show changes in sea level greater than 0.25 m over this timespan along the south-east corner of the continent and in Torres Strait, both regions that are dominated by large-scale current eddies. Note that this range in sea level elevation, occurring over a period of three months, overlaps with the lower range of values in the Villach Greenhouse prediction.

Forecasting Sea Level Rises in the Next 40 Years

The fact that sea level varies considerably in normal circumstances has important consequences in projecting accelerated rises in sea level postulated under the Greenhouse effect. Firstly, a worldwide change in sea level height due to Greenhouse may be difficult or almost impossible to detect because of the natural spatial and temporal variability that is inherent in sea level records (Bryant 1987). For instance, between Korea and the Pacific coast of Japan, sea level rates not only change sign but also diverge by 30 mm yr^{-1}. The consequences of the postulated global rise in sea level will differ due to this spatial variability, much of which appears related to tectonic changes and to a lesser extent climatic influences. The latter factor dominates Australian sea level behaviour.

Secondly, temporal variability makes the rapid detection of global changes difficult to measure. The inherent noise level of globally averaged sea levels is about 39 mm. Seasonal changes reach 0.6 m in the Bay of Bengal while inter-annual variations across the Pacific associated with the Southern Oscillation can be as high as 40 cm. The proposed increases in sea level of 0.2-1.4 m in the next 40 years under Greenhouse warming imply rates of increase of 4-28 mm yr^{-1}. This implies that at least a decade of sea level data collection is necessary before Greenhouse-induced sea level rises will become evident. Within Australia, it is generally accepted that sea level can fluctuate at a weekly to monthly level by 0.2-0.3 m, and at a decadal level by 0.1-0.15 m. With this degree of variation and the historical evidence for rates of rise as great as 6-7.5 mm yr^{-1}, it will be extremely difficult within Australia to discern a Greenhouse induced sea level rise with certainty for at least two decades.

The higher Villach sea level predictions of 1985 are now being lowered. Even under predicted surface air temperature increases of 2-4°C by the year 2085 AD, twice the period of the Villach prediction, sea levels may only be 0.28-0.66 m higher than at present (Van der Veen 1988). The Commonwealth Secretariat has proposed that sea levels will rise only 0.17-0.26 m in the next 40 years following at most a global warming of 1-2°C (New Scientist, 7 October 1989). The reason for these lower values is due to increased snowfall in polar regions under the enhanced warming theorized to occur there in a warmer Greenhouse world. These temperatures will not be enough to accelerate ice-cap melting; however, they will greatly enhance the capacity of cold polar air to hold moisture, which will precipitate easily as snowfall over adjacent ice sheets. In Australia, a recent meeting of experts, held on 3 October 1989 in Melbourne and sponsored by the CSIRO and the National Academy's International Geosphere and Biosphere Program, proposed increases of 0.2-0.3 m with an allowance of a ±0.1 m leeway to include variability between tide gauges around the Australian coastline. It is being recognized that regional predictions of sea level change due to Greenhouse warming are more important than global predictions.

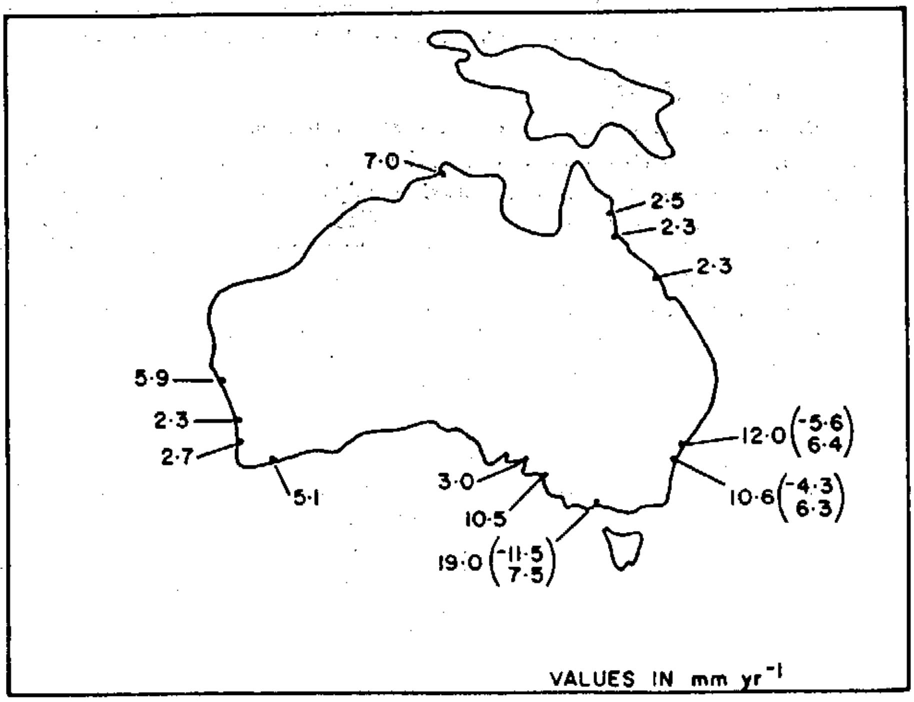

Figure 3 Maximum changes in annual Australian sea levels for any 15 year timespan.

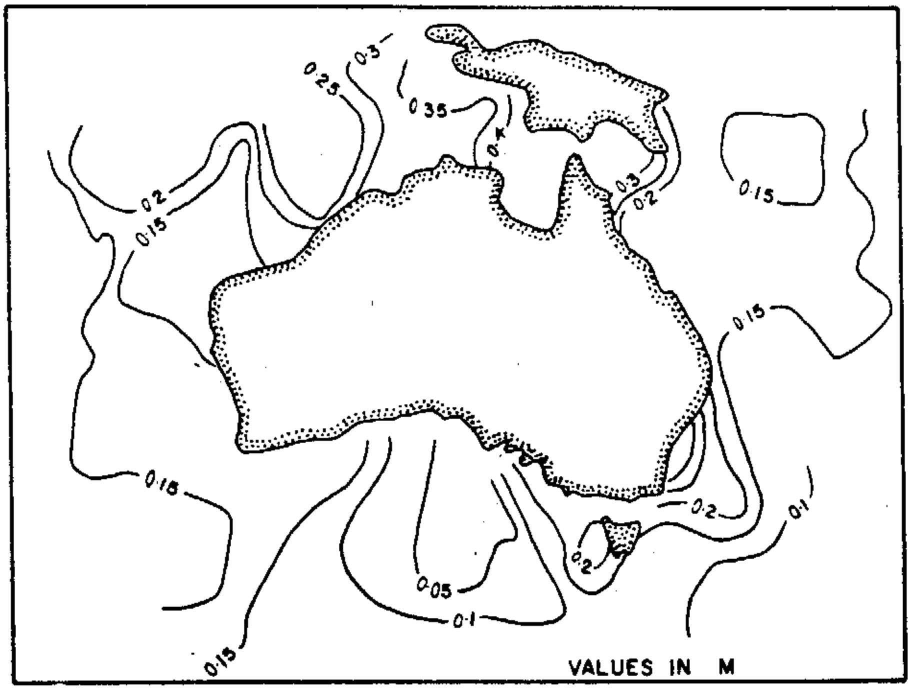

Figure 4 SEASAT residual sea level variations in the Australian region, July-October 1978.

WETLAND RISKS UNDER GREENHOUSE WARMING

Coastal Inundation

Greenhouse sea level predictions range within a continuum that includes at its lower end long term values of sea level rise, and at its upper end the extreme levels found at present in storm surges. Table 1 summarizes the existing contributions of various phenomena to extreme sea levels along the New South Wales coastline. These values will differ for other parts of the Australian coastline, and especially for those parts affected by tropical cyclones. Many of the variables in Table 1 are relatively common and have occurred together during east coast storms. Shorelines on the east coast within 5 m elevation of Indian Spring Low Water (which is approximately 1 m below Australian height datum) are inundated periodically during storms. Coastal inundation in the short term can reach very high levels in embayments along the east coast, even where tropical cyclones are not important. To my knowledge, the maximum incursion of salt water measured along the NSW coastline occurred at Pearl Beach, Broken Bay, on 25 May 1974, when water surged between houses built on a backing coastal dune having a measured elevation of 7 m above Indian Spring Low Water. Some of the elevations listed in Table 1 are certainly underestimated. For example, a storm surge elevation of 1 m is conservative, and certainly so for harbours. Additionally, while the maximum tsunami recorded at Sydney had a height of 1.07 m (10 May 1877, originating in Chile), there is geological evidence to suggest that tsunami with elevations of at least 2-3 m have affected the east coast, and speculation that tsunami greater than 10 m in elevation could affect the north-west coast of Australia (Boughton, pers. comm. 1989). If present day planning were to take into account these extreme sea levels it would minimize the effort required by governments to adapt later to elevated Greenhouse sea levels.

	MAXIMUM WATERLEVEL ELEVATION		
PROCESS	**Open Ocean**	**Open Estuary or Bay**	**Barrier Lagoon**
King tides[1]	2.0	2.0	1.5
Storm surge	1.0	1.0	1.0
Wave set-up	1.5	0.5	0.05
Wave run-up	3.0	4.0	0.05
Natural long-term climatic variability	0.2-0.3	0.2-0.3	0.2-0.3
Shelf waves	0.2-0.3	0.2-0.3	0.2-0.3
Tsunami (rare but certainly possible)	2.0	3.0	0.0
Seiching	0.5	2.0	0.2
River runoff	0.5	1.0	3.0
Maximum shoreline inundation[1]	5.0[2]	7.0[3]	4.0[4]

[1] above Indian Spring Low Water (0.0 m) which is 1.0 m below Australian Height Datum

[2] many cases during May-June 1974 and 1978 storms

[3] Pearl Beach, Broken Bay, 25 May 1974

[4] Wyong River, Lake Macquarie, May 1974.

Table 1 Maximum elevations in Sydney sea level due to various geophysical factors.

Rising Sea Levels in Enclosed and Open Coastal Systems

One of the more complex problems with sea level rise is the fact that estuaries, harbours and tidal lakes will not respond in a similar manner to the open ocean. In the United States, sea levels at tide gauges along the open shoreline are rising 1.8 mm yr^{-1} faster than those inside embayments and harbours even though the distance between gauges is negligible (Committee on Engineering Implications of Changes in Relative Sea Level 1987). This difference is greatest where sea levels are rising by more than 10 mm yr^{-1}. No explanation can yet be put forward for the difference. This facet has not been researched within Australia where a different phenomenon exists. Mean water levels in barrier lagoons are elevated relative to the adjacent ocean. In New South Wales, there are over 130 coastal waterbodies (West *et al.* 1985) and in many of these tidal levels are elevated above mean sea levels in the adjacent ocean. This condition is best exemplified at Lake Illawarra which is tied to the ocean by a 1 km long channel which averages only 1-2 m in depth, and which can be partially blocked from the ocean by beach accretion (Public Works Department New South Wales 1982). Overall, the mean lake level in Lake Illawarra is 0.3 m higher than mean sea level for three reasons. Firstly, the lake retains freshwater for periods of up to seven days after major floods. This accounts at most for one third of the superelevation. Secondly, tides within the lake tend to lag those in the ocean. Flood tides race up the deep channel but progress slowly into the lake because of its shallow depth. The ebb tide is not as strong, because bottom friction effects must be overcome before the tidal volume can return to the ocean. While the flood and ebb flow volumes balance, the lake level remains higher for longer on the ebb to compensate for the additional bottom friction effects. Finally, sea levels on average may be raised as much as 0.05-0.15 m near the tidal entrance by wave set-up. This will tend to pond water in the lake.

The effects of Greenhouse warming will have positive and negative feedback on these tidal lake levels and consequent wetland response along bordering shorelines. If sea level rises 0.2-0.3 m within the next 40 years, tidal channels into lakes may become freer flowing and lake levels will drop. Thus lakes along the New South Wales coast may be able to accommodate any change in sea level up to and including a 0.3 m rise. Increased rainfall under Greenhouse warming may either negate this drop in lake level or it may enhance flow through the tidal inlet, deepening it and aiding the drop in lake level. Finally, increased wave set-up because of increased storminess could raise lake levels. The resultant effect is complex, and only close monitoring of lake levels referenced to a nearby open ocean tide gauge will permit the effective rate of sea level rise in these environments to be determined.

Increased Storminess, Erosion and Sedimentation

Warming of air temperatures by 1-2°C in the Australian region could increase sea levels in the Coral Sea due to thermal expansion. This could lead to intensification of the East Australian Current, which would warm sea surface temperatures 100-200 km offshore from the New South Wales east coast for a longer period of the year. However, inshore upwelling of cold water at temperatures similar to those found at present would continue. The inshore sea surface temperature gradient would thus be increased, possibly leading to more frequent storminess through the generation of east coast lows. Not only does sea level in eastern Australia rise during periods of storms, but shoreline erosion increases (Bryant 1988b). In addition, seagrass beds, fringing mangroves and saltmarshes within more protected environments would be at risk, especially if wave heights were to increase overall. Such large-scale erosion would result in increased turbidity within bays, both from resuspension of sediment originating locally, and from increased discharge in streams and rivers flowing to the coast. Such turbidity could lead to increased sedimentation rates in quiescent environments, smothering seagrasses or reducing the incident light critical to their survival.

Favourable Wetland Responses

The risks to ecosystems from rising sea levels are not all negative. Saltmarsh communities under favourable conditions can rapidly prograde seaward and accrete vertically (Davies 1980, Bird 1984). The increasing rise of ground water levels and salinization of backshore environments will provide conditions which are favourable to the landward migration of wetland communities even under the most extreme conditions. For instance, Wanless (1982) has noted that many marine ecosystems occupying estuaries along the east coast of the United States had to migrate shoreward, from the edge of the continental shelf to their present locations, during the Holocene transgression at the end of the last ice age, under sea level rises which will match the extreme values forecast under Greenhouse warming in the next 40 years. Nowhere is this fact more evident in eastern Australia than at Bulli, south of Sydney. Here, Jones *et al.* (1979) have dated a mature mangrove stump at 7200 years BP, the earliest evidence found for the Holocene transgression reaching present sea levels along the New South Wales coast. Mangroves were able to keep pace with rates of sea level rise of the order of 15 mm yr^{-1}, well within predicted rates under Greenhouse warming over the next 40 years. At present, in Port Stephens, mangroves are actively re-colonizing land that was cleared and drained at the turn of the century. Given a chance, mangrove and saltmarsh species are vigorous re-colonizers.

Planning for Wetland Protection

A major problem does exist if wetlands have no room to retreat. There are at least three general planning responses to overcome this problem (Bryant & O'Connor 1990). Firstly, and most obviously, is the application of strict zoning to establish buffers permitting the shoreward retreat of wetlands and intertidal ecosystems. The strict zoning option is restrictive, unpopular and probably unwise. It easily puts government bodies in a no win situation, and might even involve hard decisions such as prohibiting any change to existing land use viewed as too close to wetlands. The second type of planning response involves the use of "time-constrained" development which in New South Wales is presently permissible under Section 91 subsection (3) (d) of the Environmental Planning and Assessment Act. "Time constrained" development simply involves giving permission for development in zones perceived as subject to inundation until such time as inundation becomes imminent or actually occurs. Consents could apply to recreational facilities, to industries with limited lifespans or to structures with life expectancies well within a 50 year time limit. Under this type of restriction, development could be removed or reassessed in the future in terms of updated data on sea level rise or extreme fluctuations. Such a planning response is more winnable, in that government bodies are viewed as taking positive action; however, by definition this response assumes that development close to existing wetlands is permissible. It also postpones the hard decision-making to a later day or generation. Finally, a more practical solution to either of the above would be the acquisition, by councils or state governments, of wetland and marine ecosystems and their shoreward zones, which can be identified as being at risk. These areas could be converted to nature reserves, marine reserves, national parks or marine parks. Responsible managers could then implement the most compatible or advantageous land uses, or incorporate the areas into buffer zones that would protect the existence of such ecosystems.

SUMMARY

The effect of Greenhouse warming upon sea level, with its attendant hazards, is not as simplistic as popularized. While a direct rise in sea levels worldwide is conceivable, it is likely that substantial regional variation will occur. In Australia, much of this variation is not due to tectonics, but to climatically induced modification of sea level behaviour. Greenhouse warming will further influence these climatic modifications by altering the distribution of pressure patterns, rainfall and temperature. These climatic changes will determine how much sea level rises on a regional basis, and the degree of daily to intra-yearly fluctuations. For Australia, this rise is most likely to be 0.25-0.3 ±0.1 m in the next 40 years. Risks to wetlands already exist under present sea level regimes. However, many of these risks could be minimized with more efficient planning that should be encouraged by all government instrumentalities. Wetlands can respond to rapidly rising sea levels; however, they can also succumb to wave erosion and increased sedimentation, which are phenomena closely associated with such rises. The recognition that existing saltmarshes, mangroves and intertidal ecosystems are worth preserving, even without considering a rise in sea level, makes it imperative that they be protected and permitted to migrate landward when sea levels do rise in the future.

A Greenhouse induced sea level change of 0.2-0.3 m in the next 40 years can have two important ramifications in terms of planning. Firstly, such rises are within the present range of variability of sea level in Australia. Secondly, and maybe more importantly, our coastline, over short timespans, already simulates sea levels in a Greenhouse world.

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