ANTICIPATED RESPONSE OF COASTAL LAGOONS TO SEA LEVEL RISE

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Abstract

Coastal lagoons, or ICOLLs (Intermittently Closed and Open Lakes and Lagoons), are a common feature on the south-east coast of Australia (particularly in NSW). Their environmental processes have evolved in response to their unique hydrological behaviour, which is dependent on both catchment and coastal processes and inputs. Of most significance to the structure and function of coastal lagoons is the condition of its ocean entrance. When open, the entrance allows for regular tidal exchange and oceanic flushing of the lagoon. When closed, however, the lagoon becomes a 'terminal lake' and captures and retains 100% of all catchment inputs.

The entrance processes of coastal lagoons, comprising the scouring or breakout stage, followed by berm rebuilding and eventual closure, are dependent on dominant coastal processes. Long term sea level rise is expected to have a significant impact on the entrance processes of coastal lagoons, which will subsequently have a cascading effect on most other environmental processes within these naturally sensitive and unique waterways.

The anticipated response of coastal lagoons to sea level rise will also depend on whether the lagoons entrances are artificially managed, both now and in the future. Many coastal lagoons are artificially 'opened' to limit the extents of foreshore inundation. Continuation of this practice in the future will also result in a change to entrance behaviour and associated environmental conditions.

Key Words: Sea Level Rise, Climate Change, Coastal Lagoons, ICOLLs, Coastal Entrance Behaviour

Introduction

Coastal lagoons, sometimes referred to as "Intermittently Closed and Open Lakes or Lagoons" (ICOLLs) are coastal waterbodies that have an intermittent connection to the ocean (that is, the ocean entrance is sometimes open and sometimes closed). Coastal lagoons have evolved from marine sands forming a barrier across natural coastal inlets and embayments when the sea level stabilised some 6000 years ago (Bird, 1994; Woodroffe, 2002).

For mostly closed lagoons, this barrier extends across the lagoon entrance in the form of a sand berm. The entrance berm is dynamic – scouring away and then rebuilding to form an intermittent connection between the lagoon and the entrance.

The hydrodynamic behaviour of coastal lagoons is unique, and defines much of the physical, chemical and biological characteristics of the environment. For mostly closed lagoons, water levels fluctuate depending on the balance of hydrologic inputs (including catchment runoff, direct rainfall and groundwater inflows) and outputs (including evaporation and seepage). When water levels exceed the height of the entrance sand berm, lagoon water will start to spill freely to the ocean. The overtopping of the sand berm causes an entrance "breakout", wherein unconsolidated sand is eroded from the entrance, forming a channel through the berm.

On-going scour caused by the outflowing water means that this channel progressively enlarges, allowing more and more water to discharge from the lagoon, until water levels within the lagoon are generally the same as the ocean levels. Depending on the final depth and dimensions of the entrance channel, the lagoon may subsequently be subject to tidal variations with tidal flows moving in and out of the scoured entrance channel.

Following an entrance breakout, beach sand is transported back into the entrance channel, causing shoaling and significant flow constriction. For most coastal lagoons in south-east Australia, the entrance will become constricted to the point of complete entrance closure, while for others (typically those with large catchments and/or natural flow controls within the entrance channel), a dynamically balanced ‘open entrance’ condition will be established. Under these conditions, the entrance channel develops as a function of the preceding catchment runoff and ocean / beach conditions, with the dynamic balance maintained, albeit temporarily between episodic flood events, by tidal flows through the channel (Elwany et al., 2003; Roy et al., 2001).

The entrance behaviour of many coastal lagoons in Australia is artificially manipulated. The minimum crest height of the entrance berm is manually lowered (via cutting of a pilot channel) to induce a premature breakout. Such activities are typically undertaken by local authorities for the purposes of controlling the maximum water levels within the lagoon. This, therefore, limits inundation extents along foreshore areas. The works are typically done as part of a flood mitigation strategy for reducing flood risks affecting low lying urban or rural lands, or critical infrastructure (eg roads, sewer pumping stations, etc).

Artificial entrance breakout is normally induced when water levels reach a pre-defined trigger value. During large and sudden rainfall and catchment runoff events, however, it is not uncommon for lagoon levels to exceed nominated trigger levels, or indeed to induce a natural breakout event by overtopping the crest level of the natural sand berm.

Coastal lagoons are recognised as one of the most sensitive types of estuaries to human intervention due to the dynamic nature of their entrances, and general lack of tidal flushing (Boyd et al., 1992; HRC, 2002). Management of coastal lagoons is therefore one of the most difficult tasks facing coastal managers today (Thom, 2004).

Climate Change and Sea Level Rise

Climate change, as a response to increased greenhouse gases in the Earth’s atmosphere, is now a widely accepted phenomenon. Impacts of a changing climate are already beginning to emerge (Steffen, 2006). For example, WMO (2005) state that, with the exception of 1996, the 10 years between 1996 & 2005 were the hottest years on record (globally averaged). In Australia, 2005 was the hottest year on record, at a temperature of 1.09°C higher than the 1961-1990 average (BoM, 2007). The past five years in Australia have been consistently significantly hotter than the 1961-1990 average (Figure 1).

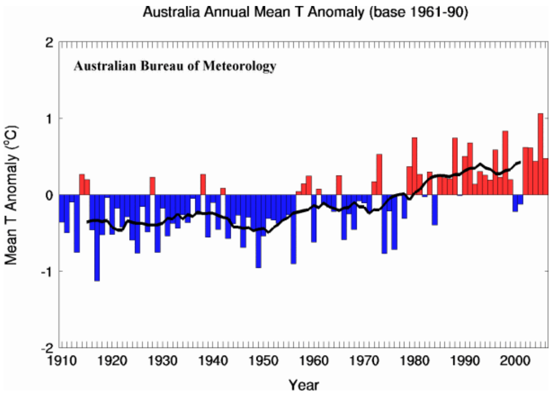

Figure 1. Australian average temperature variation, 1910 – 2006 compared to 1961-1990 average, black line shows running 11 year average (Source: BoM, 2007)

Mean sea level, on a global scale, has been increasing over the past century, due primarily to the thermal expansion of the oceans as ocean temperature has increased (Cabanes et al., 2001), as well as glacial melting (Walsh et al., 2002). Over the past 50 years or so, the widely adopted average sea level rise has been approximately 1.8mm/yr (Walsh, 2004; Church et al., 2005). Sea level rise has not occurred consistently, however, with the most recent trend (since the early 1990s) having an accelerated rise or around 3.4 mm/yr, as measured by satellite data (Figure 2).

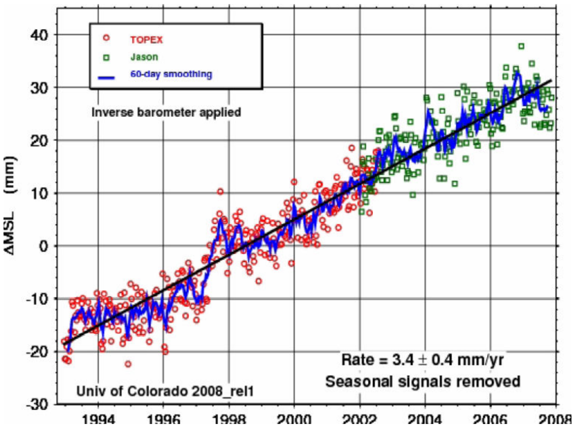

Figure 2. Global Mean Sea Level Rise, as measured by NASA satellites (Source: University of Colorado, 2007)

It is expected that mean sea level will continue to rise in the future. IPCC (2007) project an increase in mean sea level of between 0.18 and 0.59m by the end of the 21st century, with the possibility of an additional 0.1 to 0.2m due to ice sheet flow. Further, CSIRO has predicted additional localised sea level rise of up to 0.12m on the east coast of Australia due to thermal effects of the East Australian Current (McInnes et al., 2007). Based on the trend measured by most recent satellite observations, it is likely that future sea level rise will track closely to the upper limit of these projections, while a level of up to 1.4m above 1990 sea levels may be possible (Rahmstorf, 2007).

Importantly, we must recognise that sea level rise will not stop at the end of this century (the limit of most reasonable projections). Indeed it is reported that the inertia of thermal expansion held within the oceans now will result in continued sea level rise for many centuries or even millennia, regardless of any future controls on CO_2 emissions or global air temperature changes. Thus, sea levels may be several metres higher than present before they once again stabilise, particularly if large land ice masses, such as Greenland, melt (IPCC, 2007). Such circumstances would re-start geomorphic evolutionary processes on the coast, including the landward transgression of coastal barriers and the associated impoundments behind them.

Impacts on coastal lagoons

As outlined before, the environmental processes of coastal lagoons are largely driven by the condition of its entrance. Meanwhile, entrance behaviour is driven by the dynamic balance between catchment runoff (rain events) and ocean wave / beach processes. Future climate change is expected to change both rainfall and coastal processes. Climate change therefore will lead to potentially wide ranging changes to coastal lagoon environments (including physical, chemical and ecological processes that underpin local ecosystems).

While there is a high degree of uncertainty with respect to projections for future change to rainfall and wave climate, future sea level rise is more certain, as discussed above. Consequently, for this paper, emphasis is given to the consequences for coastal lagoons resulting from projected sea level rise.

Increase in Low Tide Level

A major change to coastal lagoons as a result of sea level rise will be an increase in low tide level. That is, lagoon water level won’t get as low as under existing conditions, following breakout or when subject to normal tidal behaviour.

For lagoons that are opened artificially (and assuming no change to definition of the existing breakout trigger level), there will be less potential storage of water within the lagoon before the trigger level is reached. This will result in a more frequent need to artificially open the entrance (ie the trigger level will be reached more quickly following rainfall events).

Further, due to the reduced hydraulic head across the entrance (ie difference in water levels between the lagoon and the ocean), the scouring processes associated with entrance breakout will be less effective. Less sand will be scoured from the entrance, leading to more rapid re-shoaling (and reclosure) of the entrance channel after the breakout event.

Upward translation of low tide levels would potentially 'drown' existing fringing vegetation (eg mangroves in mostly open coastal lagoons). Also, the increase in low tide levels would potentially elevate local groundwater tables around the lagoon foreshores.

Increase in Typical Lagoon Depth

The typical water depth within the lagoon will increase due to the increase in low tide (and high tide) levels. This may have impacts on benthic ecology, which has already adapted to existing light conditions, and geochemical processes within the sediments.

Greater typical water depth over marine and fluvial deltas will likely result in vertical accretion of these primary deposition areas. Such accretion is expected to occur contemporaneously with the rate of sea level rise (ie, up to ~10mm/yr).

Increased lagoon depths will theoretically reduce the potential for mixing by wind driven circulation and stirring of fine bed sediments. This may lead to a greater potential for stratification, particularly within existing deeper areas of the lagoon.

Increased water depths, particularly within entrance channels, may also diminish the impact of specific flow controls, such as shallow rock shelfs and bars. If these controls currently help maintain a mostly open entrance condition, then the lagoon may adopt a greater tendency for natural closure. Any changes to the connectivity between the ocean and the lagoon (because of reduced breakout frequency) may affect the tidal flushing capacity of the lagoon and the oceanic recruitment and dispersal behaviour for fish, prawns etc.

Shoreward translation and increase in berm height at entrance

It is well understood that an increase in mean sea level would result in an upward and landward translation of ocean beach profiles (Bruun 1962, Dean and Maurmeyer 1983, Hanslow *et al.* 2000). With respect to coastal lagoons, a sea level rise will cause the entrance sand berm to move inland and to build up to a higher level relative to local topography. The increase in berm height is expected to match the increase in sea level rise, given that the berm is built primarily by wave run-up processes (Figure 3).

The increase in entrance berm heights would be most apparent for mostly closed coastal lagoons. For such systems, lagoon water levels would therefore need to reach a higher level before inducing a natural breakout to the ocean (in the absence of artificial intervention) (Haines, 2006; Haines and Thom, 2007). As the foreshores around lagoons are generally flat, the lagoon would actually store more water before a breakout occurs (as there is a non-linear relationship between coastal lagoon volume and water level). Therefore, *ceteris paribus*, the frequency of breakouts would reduce. Potential exacerbating this outcome would be an increased evaporation from coastal lagoon given its larger water surface area, and the higher air temperatures resulting from future climate change.

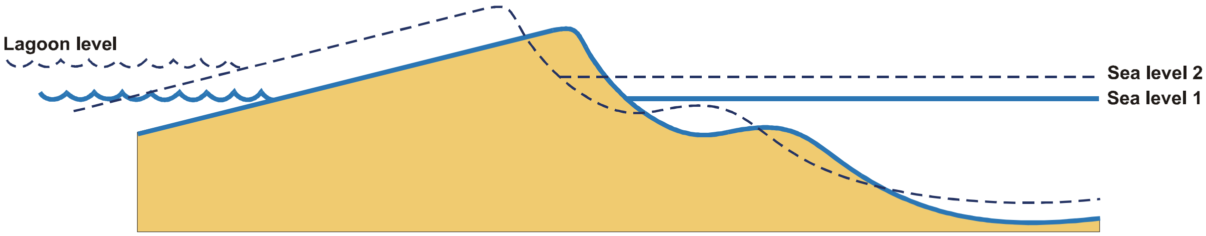

Figure 2. Shoreline response to increasing sea level (Source: Hanslow *et al*., 2000)

Elevated water levels within coastal lagoons, as a consequence of higher entrance berm levels, or higher tide levels, will potentially result in a landward migration of fringing lagoon vegetation. If vegetation communities cannot migrate upslope, however, due to obstructions or topography, then the vegetation communities may be lost altogether.

Altered Entrance Morphodynamics

An increased mean sea level will alter the existing dynamic balance of coastal lagoon entrances, which may change the proportion of time that the lagoon is open or closed. Depending on the position of the coastal lagoon entrance within the coastal compartment, broadscale responses of adjacent ocean beaches to sea level rise may result in more, or less, sand availability within the entrance channel. An overall increase in water level is also likely to induce accretion, and possible landward progradation, of the marine flood tide delta.

The tidal range within a coastal lagoon, when the entrance is open, is dependent on the flow constrictions imposed by the entrance. Under higher sea level, and hence higher lagoon level, conditions, the same tidal prism (ie the total volume of water held between low tide and high tide, which moves into and out of the lagoon) can be met by a smaller lagoon tidal range (given the larger lagoon surface area under higher water level conditions). Therefore, the increase mean sea level will not automatically translate to an equivalent increase in lagoon water level.

Entrance morphodynamic processes involve a complex interplay between beach processes (in particular, longshore sediment transport processes), tidal flows, and episodic rainfall-induced breakout or entrance scouring events. Consequences of sea level rise on all these processes is difficult to predict and will most likely involve site-specific responses.

Conclusion

Climate change is expected to have a wide range of impacts on coastal lagoons. Sea level rise is arguably one of the most predictable climate change variables. Future sea level rise of up to 0.91m (McInnes et al., 2007), or even up to 1.4m (Rahmstorf, 2007) could be expected by the end of this century. Sea level rise will have notable impacts on the behaviour of coastal lagoon entrances, which will potentially affect the fundamental structure of the lagoon ecosystem.

Whilst it is relatively straightforward to assess the 'theoretical' impact of sea level rise on coastal lagoons, it is more difficult to quantify the potential magnitudes of change. Also, it is imprudent to consider the impacts of sea level rise in isolation to other potential climate change variables, such as changes to rainfall, wave climate and temperature. When considering the full range of possible impacts, it may be possible that the impact of one climate variable could offset the impact of another, resulting in a net no change; or indeed that the impact of one variable may exaggerate the impact of another, making the result much worse than initially projected. As such, it is difficult, if not impossible, to predict the likely result on coastal lagoons processes once all factors are taken into consideration.

Overall, it can be concluded that climate change is likely to have a significant and fundamental impact on coastal lagoons in a range of different ways. Quantifying such impacts, however, would require site specific analysis, and a better appreciation of the likely change to some climate parameters as such changes start to manifest in the future.

References

Bird, E.C.F. (1994) "Physical setting and geomorphology of coastal lagoons" *In*: B. Kjerfve, ed. *Coastal lagoon processes* Amsterdam: Elsevier, 9-39

Bruun, P. (1962) "Sea level rise as a cause for shore erosion" *Journal of the Waterways and Harbour Division*, ASCE, pp 117-130

Bureau of Meteorology (BoM) (2007) "Timeseries Australia climate variability and change" [online] Available http://www.bom.gov.au/cgi-bin/silo/reg/cli_chg/timeseries.cgi [accessed

24 September 2007]. Bureau of Meteorology, Australian Government

Cabanes, C., Cazenave, A., Le Provost, C. (2001) "Sea level rise during the past 40 years determined from satellite and in situ observations" *Science* **294**, 840-842, 26 Oct., 2001

Church, J. A., White, N. J., Arblaster, J. M. (2005) "Significant decadal-scale impact of volcanic eruptions on sea level and ocean heat content" *Nature* **438**, 74-77 (3 Nov., 2005)

Dean, R. G. and Maurmeyer, E. M. (1983) "Models for beach profile response" *In*: P. D. Komar, ed. *CRC Handbook of coastal processes and erosion* CRC Press, Boca Roton, Florida, 151-165

Elwany, M. H. S., Flick, R. E. and Hamilton, M. M. (2003) "Effect of a small southern Californian lagoon entrance on adjacent beaches" *Estuaries* Vol **26**:3 June 2003, pp. 700-708

Haines, P. E. (2006) Physical and chemical behaviour and management of Intermittently Closed and Open Lakes and Lagoons (ICOLLs) in NSW. Gold Coast, Queensland: Griffith University, Ph.D. thesis, 505p.

Haines, P. E. and Thom, B. G. (2007) Climate change impacts on entrance processes of intermittently open/closed coastal lagoons in New South Wales, Australia. *Journal of Coastal Research* SI50 242-246

Hanslow, D. J., Davis, G. A., You, B. Z. and Zastawny, J. (2000) "Berm heights at coastal lagoon entrances in NSW" Proc. 10th ann. NSW coast. conf., Yamba

IPCC (2007) Contributions of Working Group I to the Fourth Assessment Report: "The Physical Science Basis"

McInnes, K., Abbs, D., O'Farrell, S., Macadam, I., O'Grady, J., Ranasinghe, R. (2007) "Projected changes in climatic forcing for coastal erosion in NSW" CSIRO, prepared for the NSW Department of Environment and Climate Change

Rahmstorf (2007) "A semi-empirical approach to projecting future sea level rise" *Science* **315** (5810) 368-370, 19 Jan. 2007

Roy, P. S., Williams, R. J., Jones, A. R., Yassini, I., Gibbs, P. J., Coates, B., West, R. J., Scanes, P. R., Hudson, J. P. and Nichol, S. (2001) "Structure and function of Southeast Australian Estuaries" *Estuarine, Coastal and Shelf Science* **53**:351-384

Steffen, W. (2006) "*Stronger evidence but new challenges: climate change science 2001 – 2005*" [online], Available: http://www.greenhouse.gov.au/science/publications/science2001-05.html [accessed 6 June 2006], Australian Greenhouse Office, Australian Government

Thom, B.G. (2004) "Geography, planning and the law: a coastal perspective" *Australian Geographer*, Vol. 35, No. 1, pp 3-16

Walsh, K. (2004) "Climate change and the coast: Science and adaptation" Proc. Coast to Coast 2004, Aust. nat. coastal conf., Hobart, 19-23 April

Walsh, K. J. E., Betts, H., Pittock, A. B., McInnes, K. L., Jackett, D. R., McDougall, T. J. (2004) "Using sea level rise projections for urban planning in Australia" *Journal of Coastal Research* **20**(2): 586-598

World Meteorological Organisation (WMO) (2005) "WMO statement on the status of the global climate in 2005" [online], Available: http://www.wmo.int/web/Press/Press743_E1.doc [accessed 11 January, 2006] WMO Press Release 743, 15 December, 2005

Woodroffe C. D. (2002) "Coasts: form, processes and evolution" Cambridge University Press, Cambridge UK, 623pp