Canute's Dilemma-Adapting to the Forces of Nature

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Abstract
While debate continues as to whether the current global warming trend is natural or anthropogenic, short term or long term, the evidence brings with it the reality that conventional engineering design practice of assuming natural forces can be conveniently described as a statistically stationary series based on relatively short term records is flawed. The climate change debate points to the need for a greater emphasis on sensitivity analysis and decisions based on consequences associated with the risks involved in establishing design criteria. This is particularly true in coastal engineering where most natural forcing functions are linked by squared laws to the consequences. The result is a need to re-think design philosophies to accommodate the uncertainties associated with a less predictable climate future. Adaptive options are essential for any project of value and/or with a moderate to long term economic life.

1 Introduction

"Let all men know how empty and worthless is the power of kings. For there is none worthy of the name but God, whom heaven, earth and sea obey". Canute was frustrated by the forces of nature. He demonstrated this to his courtiers by an unsuccessful attempt to turn back the tide. Adapting to climate change and managing the forces of nature, turning back the tide, is the challenge now facing today's coastal engineers.

Starting three decades ago, momentum has been progressively gathering around the belief that the world is in a global warming phase. Further, that this current phase of warming commenced in the mid 1800's and has been developing exponentially during the post Industrial Revolution era. The warming trend has been linked to an increase in greenhouse gasses in the atmosphere resulting from man's activities. The Publications of the United Nations Intergovernmental Panel on Climate Change and, closer to home, the Australian CSIRO supporting this position are too numerous to attempt to reference in this paper.

Interestingly the post Industrial revolution period just happens to coincide with the thawing from the last mini ice age. So the question arises as to whether the global warming and sea level rise trend currently being experienced is simply part of larger natural fluctuations or whether it has an anthropogenic cause. Further, as to whether the current trend may reverse in the near future. Some recent publications, for example Plimer (2009), argue the case against anthropogenic causes and also question whether the recent warming trend will continue. Of importance to coastal engineers however is that all parties in the debate and all the scientific evidence that has been presented by both sides demonstrates the global climate has been very unstable over millennia and that the last 6,000 years has been marked by being the most stable period that can be recognised. Further, even during that 6,000 years there have been significant oscillations in the climate. These oscillations have exceeded the changes recorded in the last 200 years. Therefore, while the debate on the status and cause of the current climate trend is fascinating and its implications undoubtedly have significant political, economic and social consequences, it somewhat defocuses attention from the fact that natural or anthropogenic, the evidence from all parties is that the world's climate is far less stable than engineers have traditionally planned for. Setting aside the debate as to whether the globe is currently warming or cooling, naturally or anthropogenically induced, from an engineering perspective there is a need to develop design philosophies and effective, viable, options for managing a far less certain climate than conventionally assumed.

The variability of the global climate can be demonstrated by examining the changes in one aspect, sea level, during the last 130,000 years. Sea level, 130,000 years ago, was between 4m and 5m higher than present. It then fell 70m before oscillating about 50m on 4 occasions between 120,000 and 45,000 years ago. At this point in time the last major Ice Age took hold and sea level started to fall until it was 130m below present 18,000 years ago. As the climate warmed sea level rose the 130m between 15,000y BP and 6,000y BP albeit in stages that included a number of reversals, before it reached approximately where it is to day (Dean et al, 1987, Short, 1993, Plimer, 2009). During that period the rate of movement of sea level was, at times, of the order 10mm per year, substantially greater than at present. As stated, imbedded within the overall sea level trend there have been many lesser oscillations lasting at times hundreds of years. For example, there was a warm period between 900AD and 1300AD during which Greenland was capable of sustaining farming and sea level was higher. This was followed by a mini ice age between 1400 AD and 1800 AD during which the entire population of Greenland was wiped out (Dean et al 1987, Diamond, 2005).). The evidence is that during the last 6,000 years sea level has oscillated up and down 1m to 2m on several occasions in response to climate changes consisting of warm and cold phases with global temperature shifts of several degrees centigrade.

In discussing global climate and sea level trends it is important to recognise that, because of the physical mass of the earth's oceans, historical sea level trends tend to reflect, and integrate longer term climate trends. The globe warms, water at first expands causing sea level rise and then some decades later ice melt from land based ice sheets further increase sea level. It should be noted that net melting of sea ice does not impact on sea level; it does however indicate global warming. While there is a considerable body of evidence on global climate and sea levels stretching back millennia, there is far less evidence on storminess and engineering scale climate; the climate to be designed for in the economic and/or realistic life of a structure or solution. Recent work by Callaghan and Helman (2008) is of assistance in gaining a better understanding. They have demonstrated that storms on the east coast of Australia over the last 138 years have been episodic rather than cyclic or random and that episodes can last several decades. Further, that the last 30 years has been a period of quiescence that is not representative of the storm potential.

It is vital that debate on long term trends does not mask the important engineering considerations of design conditions associated with the shorter term. Traditionally coastal engineering has conveniently assumed that natural occurrences such as storms with their associated rainfall, waves, storm surge and coastal erosion can be ranked in a statistically stationary series based only on limited recent experience, and that mean sea level is a constant. Given these now obvious major flaws in contemporary design philosophy it is important to recognise a new approach is required that seeks to achieve the desired outcomes in a less certain environment. That is, an approach which determines a probability of outcome based on a sensitivity testing of scenarios and which, through a risk analysis, takes into account the consequences of failure. Designs that have a catastrophic failure mode should be limited to low cost or short lived structures. Flexible, adaptive solutions and/or designs with a progressive failure mode are required for which the likely life of the solution/structure is within time frame for which reasonable predictions can be made and the consequences of solution/design failure can be accommodated; solutions that can survive in a less well defined environment.

2 Open Coast Climate Change Impacts

On exposed coastal beaches a predicted mean sea level rise of say 0.9m over the next 100 years in itself is rather minor. Generally this is less than 50% the present tidal range and in some locations, less than 10%. It is the potential re-adjustment of the beach profile with associated coastal recession that needs to be catered for. Other factors include: the shifts in weather patterns and the resultant changes to net wave energy flux and therefore long shore drift rates for long open coast beaches and changes in beach alignment for embayed beaches; alterations in wind strength and persistence in shallow seas such as a strengthening of South East Trades in Torres Strait: changes to coastal shelf currents and the implications for outfalls (natural and man made); increased erosion events due to more frequent storms with their associated storm surge and wind setup combined with the potential for increased coincidence of severe events with high tides and; the emerging sleeper, the loss of beach sediment volume on beaches with a high shell content as the acidity of coastal waters change.

Bruun, in 1962, proposed an empirically based relationship between sea level rise and coastal recession based on the impact of long term water level rises on the shorelines of the Great Lakes in USA. The application of Bruun's model to various locations was summarised by Bruun and Schwartz (1985) and adapted by Gordon (1987) to the NSW coast in the simplified form Recession = 100×Sea Level Rise. That is a 0.9m sea level rise would be predicted to produce 90m of coastal recession albeit there is a lag between the rise and the shoreline response, depending on the frequency of storm events. While the Bruun model may have limitations due to its 2 dimensional nature and its generalized application to a wide variety of different coasts, it does provide an insight into the order of magnitude of coastal recession associated with a relatively modest rise in sea level.

Climate change, warming or cooling, implies potential shifts in the locations and intensities of high and low pressure systems. That is a shift in the wind fetches that create waves. Given that sedimentary shore alignments are an integrated response to the direction and magnitude of wave energy, the net energy flux, any change in the intensity and/or overall location of the wave generating systems, the high and low pressure tracks, will produce a net shoreline response. As with the coastal recession response to increased sea levels there is a time lag between changes to the net energy flux and the shoreline response. It is also important to recognise that while climate change may increase wave energy at a particular location, the shifts in pressure systems may result in an offsetting reduction in the net angle of wave attack. Conversely, reductions in wave energy at a location may be countered by increases in net wave attack angle, hence a region which it might be assumed will be less prone to erosion due to reduced energy may be equally, or more effected, as a result in a shift in net wave attack angle. On long sandy coastlines experiencing net littoral drift a change in the net energy flux will increase, or decrease the net annual longshore drift. It is instructive to examine the energy flux method (SPM, 1984) as this demonstrates the potential sensitivity of longshore transport to changes in net breaker angle and to wave height. A change in net breaker angle from say 5 degrees to 7 degrees, for example, using the SPM methodology will increase the transport by 30%, or a change in representative wave height from say 4m to 5 m will increase the transport by 56%. As with the Bruun profile calculation it is possible to argue the merits of the SPM methodology, however it does provide a simple and rational guide to the impact of shifts in the net wave climate.

For embayed beaches a shift in net energy flux will be reflected in the re-alignment of the beach and nearshore coastal process systems within those embayments. For the purpose of discussion, three categories of embayment are considered: deeply embayed short beaches; embayed longer beaches that will remain embayed even if re-alignment of the coastal sediments occurs: and beaches that will no longer be constrained by their headlands and associated offshore reefs if coastal re alignment occurs. The shoreline alignment of deeply embayed short beaches tends to be dominated by the diffraction effects around headlands hence even a significant shift in net energy flux may have little impact. On longer beaches however the diffraction effect is constrained to the proximity of the headlands and the remainder of the beach alignment determined by wave refraction. Using a simple approach to illustrate potential impacts, the straight parallel contour coast refraction diagrams of Johnson et al (1948) show that for a 5º shift in offshore net energy flux there is approximately a 1º change in angle at the beach. A 1º change in beach alignment on say a 3km beach (Narrabeen, NSW), and assuming it tilts evenly around the centre, produces 26m recession at one end and a similar amount of accretion at the other. On a 30Km contained beach (say Newcastle Bight, NSW) the recession at one end would be of the order 260m. Again a simplified approach has been used to illustrate the fact that relatively small changes in the location of weather patterns resulting in shifts in net offshore wave approach direction can result in significant recession issues for back-beach assets, particularly those towards the ends of embayments. For beaches where a change in net energy flux produces a re-alignment that initiates an escape of material from that embayment, not only will the beach re-alignment result in shoreline recession, but the recession will be enhanced by the net loss of material from the embayment.

Climate Change induced alterations to wind regimes such as a strengthening and/or increased persistence of Trade Winds can have a significant impact on water levels, particularly in shallow seas. For example the increase in persistence and strength of the SE Trades on Torres Strait coastlines is demonstrated by the reported increase in peak water levels due to set-up of 0.4m in 53 years on the low lying island of Saibai (Gordon, 2008). Although there are limitations to the absolute reliability of the data, a village of 500 people that did not experience flooding 50 years ago is now inundated approximately 10 times per year. Saibai may be the first Australian Community to have to abandon their island home.

Ocean outfall designs are predicated on the dilutions achieved by both near field and far field mixing and dispersion. While the near field mixing is dominated by the design characteristics of the diffusers, the far field dilutions are a product of coastal currents. If climate change results in an increase in shelf/coastal currents then the performance of the outfall is likely to be enhanced. If on the other hand there is a reduction in persistence or strength of such currents then the performance will deteriorate and it may be necessary to modify the diffusers to meet discharge criteria. Changes to wave climate may also impact on outfall structures such as sea bed pipes and risers. Rivers are nature’s outfalls. Their distribution of sediments and nutrients to the shelf and hence their influence on coastal fisheries may alter if coastal current systems are altered by changes to the climate which alter the driving systems for those currents.

Clearly if climate change predictions include increased storminess in an area then increased erosion events can be expected. The severity of these events may however increase out of proportion with the increase in frequency and or magnitude of the storms resulting in net shoreline recession. Storms not only generate eroding waves but they also produce storm surge due to wind and pressure set-up which super elevates the water surface against the coast, resulting in higher than predicted tides and hence inundation of the beach berm. This allows the storm waves to directly attack the back beach and dunes resulting in enhanced erosion as was dramatically demonstrated by the multiple storms that occurred in 1974 on the NSW coast. Increased frequency of storms means less time for berm and dune recovery hence again, greater opportunity for storm erosion thereby producing a compounding effect. The greater the frequency of storms also means the greater the probability peak wave attack will coincide with spring tides, further enhancing the opportunity for storm waves to directly attach back beach areas resulting in net recession.

Recently the potential impacts of climate change induced acidification of coastal waters on selected Sydney beaches was investigated (Laxton and Laxton, 2009). Carbon Dioxide is highly soluble in sea water forming carbonic acid. Based on the work of Guinotte and Fabry (2008) the Laxtons pointed out that, given a number of Sydney's beaches are 30% shell, an increase in ocean PH could in time result in a significant reduction of beach sediment volume with associated coastal recession. In reaching this finding the Laxtons also cited increased acidification as a cause for the production of weaker shells that could be expected to break down more rapidly with some organisms no longer being effectively able to produce shells at all in the future.

3 Estuarine Climate Change Impacts

In estuaries the climate change factors raised in the discussion on the open coast will also have some effect. However unlike the open coast where storm waves and coastal erosion dominate, rises in mean sea level and super elevations of water levels due to storm surge are likely to be the major factors producing adverse impacts in estuaries.

4 Options – Open Coast

The principal man-made assets on the open coast are seawalls, breakwaters, groins buildings and infrastructure. The main natural assets are beaches, dunes and cliffs.

Seawalls, breakwaters and groins can be subdivided into three categories: rigid structures; semi-flexible structures and flexible structures. The term seawall is used in this paper to denote a structure that forms the interface between coastal processes and land; seawalls include revetments. Breakwater is the term used to describe walls with water on both sides such as harbour fortifications or training walls for river entrances. Groins are structures constructed to interrupt littoral drift. Rigid structures tend to have a catastrophic failure mode once design conditions are exceeded. Further it is often difficult to viably retrofit modifications aimed at dealing with increased loadings. Such structures are therefore not readily adaptable to climate change situations where wave heights and/or persistence of storms will increase. They can also be susceptible to even modest changes in water level, such as sea level rise and/or increased storm surge, particularly in situations where overtopping can be critical. For example a solid seawall protecting an on-shore coal loader located immediately landward of the wall, or a caisson breakwater with a wharf on its leeward side. Existing rigid structures are a class of asset and asset protector which is potentially highly susceptible to adverse changes in wave climate and water levels. Rigid structures are not a desirable option for future use as seawalls or breakwaters. For minor structures such as some beach groins that may have a relatively short life, rigid structures may still provide an acceptable option. Semi rigid structures include those faced with interlocking blocks or pattern placed armour units. They can be retrofitted to increase structure height to cope with increased water levels, particularly in seawall applications, although generally no so for breakwaters. Pattern placed or interlocking armour is however usually designed for specific wave criteria that if exceeded results in catastrophic structural failure. Given that armour size is a function of wave height squared, semi rigid structures are sensitive to even a modest increase in wave conditions above design. As with rigid structures, semi rigid structures are undesirable as an adaptive option for the future. Flexible structures are those constructed of rubble material faced with randomly placed rock or concrete block units. If increased toe scour occurs due to increased wave climate, the structure settles. If the structure is overtopped it can be "topped-up" with suitable armour. If the protective armour is no longer of sufficient size to cope with increased wave energy the slope either re-adjusts (often requiring further topping up) or larger armour can be placed on top of the existing slope. The process of adaption to an increasing wave climate can be repeated over time, as required. A flexible design structure philosophy is therefore the preferred approach for future structures and can be used to upgrade both rigid and semi-rigid structures by progressively burying them in random placed armour.

Buildings can be divided into the same three categories however their adaptability is significantly different. The rigid buildings are those constructed of concrete or masonry. They may have piled foundations or conventional footings/slabs. Such buildings are not readily adaptable to the adverse impacts of a changing wave and water level climate with an associated beach or cliff recession. Sea walls may provide protection for a time but even flexible walls have their limitations in this application. Seawalls eventually become undermined and overtopped. Further, if the armour unit size is not upgraded ahead of time, units near the crest can become missiles during sever storms threatening the structural integrity of the buildings. Finally the elevated water levels due to sea level rise and increased storm surge will eventually enter the buildings unless they are sufficiently set back to allow for the construction of a secondary flood barrier. Semi-rigid buildings, for example, de-mountable or light weight timber framed buildings can be removed and/or elevated to adapt to a changing coastal situation. Generally such buildings, including houses and surf clubs, have an economic design life which can be realized within a time frame that is in keeping with the pace of climate change. Buildings such as public facilities can be of a design form and life that is in keeping with their location and their susceptibility to the adverse impacts of climate change. Flexible structures such as mobile homes and portable or re-locatable buildings are well suited to an environment with an uncertain future. In developing building solutions in the coastal zone it is vital to recognise that coastal recession and inundation are natural phenomena that have been occurring, on and off, for millions of years. They only become problems when assets are placed and/or designed inappropriately. A "prevention is better than cure" approach therefore dictates a flexible, adaptive philosophy.

Infrastructure in coastal areas typically takes the form of roads, parks and services such as gas, electricity, water and sewerage. Historically the back beach dunes have provided a haven for easy construction of this infrastructure. Roads can be a particular problem especially if they service development where, if the road is not maintained, the development looses its access. In this case there is a tendency to defend the road by raising it and providing seawall protection. This can result in the undesirable by-product of drainage problems for landward development. Where possible a preferred option is to relocate the road and/or access inland. Infrastructure associated with parks normally has a relatively short economic life and should be designed in accordance with the future uncertainty of the area in which the park is located. Generally service infrastructure has a set economic life and with responsible planning can be progressively re-located as required, but should be designed in the future to facilitate adaptability and, have built in redundancy.

Beaches and dunes, as naturally flexible systems, will adjust according to the climatic change impacts they are exposed to. When beaches are backed by assets or infrastructure, there are three choices to deal with increased shoreline recession and/or inundation: withdraw, defend with hard structures or nourish. Withdrawal means loss of assets and infrastructure; a difficult social and economic challenge but a method of retaining a public foreshore. It is a suitable philosophy for sparsely developed foreshores and/or where the development is of low economic value. Defending with hard structures retains the asset for the time being but is expensive and results in the progressive loss of the beach and dunes and the eventual loss of the asset. It is a viable option where the assets are high value rigid structures whose economic life has not yet been achieved and where the foreshore is in private ownership. Beach nourishment, if undertaken on a major scale, can provide both protection for back beach assets and infrastructure while retaining the beach and dunes. The nourishment option is adaptable and can be repeated, as required. Because of the scale required for nourishment to be viable it is most suited to situations where the back beach area is densely developed with rigid structures, there is major infrastructure potentially under threat and/or the beach is a highly valued asset; public, private and/or commercial.

Cliffs, including bluffs, present a particular challenge. Increased storminess and ocean water levels are likely to increase recession of the cliff/bluff base while increased rainfall can assist in destabilizing the structure of the cliff/bluff. Depending on the circumstances it may be possible to protect cliff/bluff toes by constructing seawalls and the cliffs themselves by intervention such as rock bolting, however cliff/bluff top assets have very little option but to consider withdrawal, particularly as cliff/bluff failures tend to be catastrophic and often unpredictable as against the more progressive type failure mode associated with beaches.

5 Options – Estuaries

While much that has been covered for the open coast applies to estuaries, the emphasis in estuaries tends to be more on the impacts of water levels rather than wave action. The challenges facing defense structures is generally of a more minor nature and even rigid structures can usually be augmented to cope with increased loading, overtopping or undercutting. Harbour and estuary based structures such as wharves and marinas have a defined economic and structural life of around 30 to 50 years. The materials used for their construction, including concrete, steel and timber, deteriorate rapidly in the marine environment necessitating their replacement. The opportunity to adjust for changed design conditions therefore presents itself in a timeframe that can accommodate any required changes. The trend towards floating marina units and public wharves assists in achieving a readily adaptive solution. Even on-shore infrastructure such as boat lift type slipways and mobile cargo handling facilities can be readily adapted to a changing environment, as the slabs on which they are based require replacement every 30 to 50 years for economic, structural and operational reasons, and the mechanical handling units generally have a life of 20 to 30 years at most. As with the open coast it is rigid buildings that pose the major problem, not so much because of potential structural damage from wave attack but rather their usability as sea level rises and storm surge increases. On low lying land that may be inundated within a 100 year period, buildings that can be readily elevated, if required, provide an adaptive, flexible option. For existing rigid structures, options to bund and/or "stop log" the buildings to extend their life should be considered. Infrastructure can be protected by retrofitting options that allow for submergence, for example, extending manholes and cable pits and bunding pumping stations. Roads can be progressively elevated as inundation affects their efficiency of use and flexible seawalls built to prevent undermining. Drainage systems and structures are special cases that require site specific solutions to address flooding of land remote from the shoreline and to cope with increased rainfall.

6 Option-"Do Nothing"

The "ostrich: do nothing" option can mistakenly have short term political social and economic attractiveness. In reality it is without responsible merit as it is clearly intergenerational negligence and becomes untenable when one runs out of sand in which to bury one's head. The option does however highlight a looming legal problem of property rights and boundaries. Doing nothing to address increased shoreline recession and water levels means that progressively public assets, both built and natural, will be lost and private property will come under threat. It is the latter that will provide "interesting times".

Private property in Australia is governed by either Old Title or Torrens Title provisions. Under old Title most properties had "High Water Mark" (HWM) seaward boundaries whereas the Torrens Title properties are defined by "right lines". That is their boundaries are fixed by surveyed lines. The concept of HWM boundaries is that they are ambulatory; they move as a property accretes or erodes. There are however two major problems with HWM boundaries. Firstly they have been traditionally incorrectly defined. The original law applied to land "overflown by the sea" and that land beyond the boundary was "dry and manorable"; land beyond the "uprush of the sea" (Gordon, 2003). Clearly this is not HWM on the open coast as this does not take into account storm surge and/or wave run up. The HWM boundary definition would appear to be an artifact of a court judgment in 1854 rather than the intent of the original law. For correct interpretation of law the original intent is paramount; clearly HWM was not the intended basis for the legal boundary between private property and "the Kings Realm" (Crown Land).

The second problem is that people have been allowed to artificially accrete their properties and to protect their HWM boundary; preventing it from being ambulatory. As sea level rises and coastal recession increases the legal standing of many HWM boundaries and associated property protection may well become a legal and coastal management minefield. Right line boundaries are clear, surveyed, boundaries that are not ambulatory and are more legally robust. The problem is however that a "do nothing" approach will encourage/force the undertaking of individual measures to protect some property at the expense of other property including public use/access to the foreshore. Eventually when a particular property becomes untenable, owners will walk away leaving the ruins to deface the coast (Gordon et al, 1979).

A further interesting complication is the ancient law of the "Public Trust Doctrine" arguably providing the general public with the right to access the coast (Gordon, 2003). This statute has been in hibernation for some time but loss of public access, as individuals seek to protect their properties, may just wake up a "sleeping giant". In summary, a "do nothing" approach while superficially attractive is likely to fundamentally challenge property rights, boundaries and public ownership of, and access to, the foreshore thereby becoming a political, social and economic nightmare instead of an easy solution.

7 Canute's Dilemma

Canute's dilemma is therefore whether to withdraw as coastal impacts of climate change become apparent for coastal assets or, to defend the realm. The latter could be seen as a hard structural solution even if flexible seawalls are utalised; however the defence could be in the form of major beach nourishment programs timed to maintain the desired coastal environment. This is not a new concept and is already practiced in Australia, Holland, USA and other countries.

"Defending" can also comprise ensuring that new developments are sited so that they will achieve their expected life before being adversely impacted by climate change. Withdrawal appears superficially attractive however it has significant social, economic and political impacts not to mention the legal complexities associated with ownership and responsibility.

Withdrawal can be contemplated if coastal development is of a flexible or semi flexible design. As an option it allows coastal lands to be beneficially utalised for as long as they are viable for the specific use, including housing. It does however imply a major shift in social culture and the laws governing the use, enjoyment and eventual abandonment of coastal lands.

As the old Chinese curse says: "may you live in interesting times."

8 References

Bruun, P. and Schwartz, M.L., (1985) Analytical predictions of beach profile change in response to a sea level rise. Z.Geomorph. NF, Stuttgard, pp 33-50

Dean, R.G., Dalrymple, R.A., Fairbridge, R.W, Leatherman, S.P., Nummedal, D, O'Brian, M.P., Pilkey, O.H., Sturges, W. and Wiegel, R.L. (1987) Responding to Changes in Sea Level, Engineering Implications. National Academy Press, USA, ISBN 0-309-3781-6, 148pp

Callaghan, J and Helman, P., (2008) Severe Storms on the east coast of Australia 1770-2008. Griffith Centre for Coastal Management, Griffith University, Australia, ISBN 978-1-921291-50-0, CD format

Diamond, J., (2005) Collapse- How Societies Choose to Fail or Survive, Penguin Books ISBN 0-7139-9862-8, 575pp

Gordon, A.D., Lord, D.B. and Nolan, M.W. (1978), Byron Bay-Hastings Point Erosion Study, Public Works NSW Report No. PWD 78026, November, 1978, ISBN 7240-2691-6, 228pp

Gordon, A.D., (1987) A Tentative but Tantalizing Link between Sea Level Rise and Coastal Recession in NSW, Australia. Proceedings of CSIRO Greenhouse 87 Conference, Melbourne, Academy of Science, Cambridge Press ISBN 0-643-04863-4, pp121-134.

Gordon, A.D., (2008) Saibai Coastal and Infrastructure Management, Coastal Zone Management and Planning P/L, Research Report No. 08/1

Gordon, A.D., (2003) The Boundaries of Ignorance, Address to the College of Law, printed in the Proceedings of the Forum, Sydney, March 2003, 16pp

Guinotte, J.M. and Fabry, V.J., (2008) Ocean Acidification and its Potential Effects on Marine Ecosystems Ann N.Y. Academy of Science Vol. 1134 pp 320-342

Johnson, J.W., O'Brian M.P. and Isaacs, J.D., (1948), Graphical Construction of Wave refraction Diagrams, US Navy Hydrographic Office, Publication No.605, January 1948

Laxton, J.H. and Laxton, E.S. (2009) The Effects of Climate Change on Beaches in Pittwater, Warringah and Manly Local Government Areas, J.H. & E.S. Laxton Environmental Consultants P/L, Research Project Pub. June 2009, 28pp

Plimer, I.R. (2009) Heaven and Earth - Global Warming: the Missing Science, Connor Court Publishing, 2009, ISBN 9781921421143, 503pp

Short, A.D. (1993) Beaches of the NSW Coast. The University Printing Service, University of Sydney, 1993, ISBN 0-646-15055-3, 358pp

SPM (1984), Shore Protection Manual, Waterways Experimental Station US Army Corps of Engineers, US Government Printing Office, Washington D.C. 4th Edition, 1984.