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Using Sea Level Rise Projections for Urban Planning in Australia

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ABSTRACT

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This study deals with incorporating predictions of sea level rise into practical municipal planning. Predictions of global mean sea level rise can be made with more confidence than many other aspects of climate change science. The world has warmed in the past century, and as a result global mean sea level has risen and is expected to continue to rise. Even so, there are significant uncertainties regarding predictions of sea level. These arise from two main sources: the future amount of greenhouse gases in the atmosphere, and the ability of models to predict the impact of increasing concentrations of greenhouse gases.

Current knowledge regarding the effect of global warming on sea level rise is reviewed. *Global mean* sea level is expected to rise by 3–30 cm by 2040, and 9–88 cm by 2100. An important remaining uncertainty is the future contribution of surface water storage (for example, lakes and reservoirs) to changes in sea level. In addition, there are also significant local sea level effects that need to be taken account in many regions of the globe, including isostatic and tectonic effects. The thermal expansion component of sea level rise is also likely to vary regionally, due to regional differences in the rate of downward mixing of heat and to changes in ocean currents.

The current state of planning for sea level rise in Australia is reviewed. While not all coastal municipalities include sea level rise in their planning schemes, the recent adoption in a number of States of new planning schemes with statutory authority creates a changed planning environment for local government. Coastal urban planning needs to take sea level rise into account because its effects will be apparent during the typical replacement time of urban infrastructure such as buildings (before about 70 years). For local planning, ideally a risk assessment methodology may be employed to estimate the risk caused by sea level rise. In many locations, planning thresholds would also have to be considered in the light of possible changes in storm surge climatology due to changes in storm frequency and intensity, and (in some locations) changes to return periods of riverine flooding. In the medium term (decades), urban beaches will need beach re-nourishment and associated holding structures such as sea walls. Changes in storm and wave climatology are crucial factors for determining future coastal erosion.

ADDITIONAL INDEX WORDS: *Climate change, coastal engineering.*

INTRODUCTION

Local governments face a number of issues when planning for future sea level rise. Sea level rise may accelerate the erosion of coastal margins, threatening land and property. It also diminishes the effectiveness of the buffer provided by the beach, bringing higher energy waves closer to the dune system. Rising seas may increase the incidence of coastal flooding, either by increasing the height of storm surges, or by acting as a higher seaward barrier restricting the escape of flood waters caused by excessive runoff. Since sea level rise is a confident prediction of climate change science, it has been the subject of numerous studies regarding its possible effects on coastal management issues.

The effect of the increase of "greenhouse" (heat-absorbing) gases has been assessed by the Intergovernmental Panel on Climate Change (IPCC; IPCC, 1996, 2001). The IPCC found that the world is warming and that man-made technological processes are increasing the amount of greenhouse gases in the atmosphere. In its Second Assessment Report published in 1996, the IPCC stated that the balance of evidence suggested a "discernible human influence on global climate", while the Third Assessment Report (IPCC, 2001) stated that "an increasing body of observations gives a collective picture of a warming world and other changes in the climate system." Nevertheless, it is important to emphasize that many of the projections of global change science are affected by uncertainties. These include not only the uncertainty caused by incomplete scientific knowledge, but also that inherent in the estimates of possible future greenhouse gas emissions. These "emissions scenarios" depend on assumptions about future global economic growth and technological change, so a wide range of such scenarios is usually given. New estimates for projected sea level rise are given in IPCC (2001).

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The main reason that this is a relevant planning issue for local government is that the time frame of likely noticeable impacts of climate change (30+ years) lies within the typical replacement cycle of infrastructure such as large commercial developments and dwellings (about 70 years). Thus planners need to take climate change effects into consideration to minimize future impacts on new infrastructure and regularly need to monitor and review sea level projections to reassess their position. Here we focus on impacts and planning in Australia, in order to provide a comprehensive overview for this country that will be of use to researchers and coastal managers.

Section 2 reviews current sea level projections for the 21st century, while local planning implications of these results are discussed in Section 3. Section 4 provides some conclusions and recommendations.

THE SCIENCE OF SEA LEVEL RISE

Introduction

By its very nature, sea level rise is a long-term concern, as the effects of climate change are slow and will take decades to become apparent. We are therefore focussing on the amount of sea level rise that will occur by the year 2040, which is nevertheless within the typical local government planning horizon for building infrastructure. Projections for 2100 are also discussed.

Projected global mean sea level rise has several main components:

- thermal expansion of the oceans caused by warming;
- the melting of glaciers and small ice caps, also caused by warming;
- the contribution of the large ice caps (Greenland and Antarctica) to sea level changes through the melting and/or accumulation of snow; and
- changes in terrestrial storage.

In this study, the factors involved in estimating each of these components are described and the latest estimates reviewed. There are also factors that can cause regional variations in sea level, including the following:

- geological effects caused by the ongoing slow rebound of land that was covered by ice during the last Ice Age (“isostatic rebound”);
- the flooding of continental shelves since the end of the last Ice Age, which pushes down on the shelves and causes the continent to push upwards in response (“hydro-isostatic effect”);
- tectonic effects caused by changes in land height in volcanically active regions; and
- changes in atmospheric wind patterns and ocean currents that could be caused by climate change.

The effects of local subsidence caused by the compaction of sediments or by groundwater extraction can be very large. For planning purposes, this factor would have to be evaluated at site-specific locations (*e.g.* BIRD, 1993).

Global Mean Sea Level Rise

It is considered likely that the sea level rise in the 20th century has been largely caused by the observed increase in global surface temperature over the same period. Sea level has risen in the past century with increasing temperatures and climate models suggest that this warming will accelerate in the future; moreover, the thermal lag of the oceans caused by their very large heat capacity means that global mean sea level would continue to rise for the next several decades or longer even if there were no further production of greenhouse gases (WARRICK *et al.,* 1996; CHURCH *et al.,* 2001). This review largely summarizes the results of CHURCH *et al.* (2001), contained in IPCC (2001), the most authoritative recent report on climate change.

Global Sea Level Rise in the Past Century: Observations and Estimates

In the past century, global average sea level has risen by 10–20 cm, as measured by tide gauges located around the world (CHURCH *et al.,* 2001). To obtain a sea level change signal appropriate for the open ocean, tide gauge data must be accurately corrected for land movements and also must be long enough to separate out the year-to-year variability that occurs in many locations. Tide gauges represent the most accurate current record of sea level, however.

Additional measurements have been made from the TOPEX/POSEIDON spacecraft (NEREM *et al.,* 1997), which uses radar altimetry. This technique gives global average sea level at an accuracy of several mm every 10 days. The results still must be corrected for isostatic movements (PELTIER, 1998), but are not affected by tectonic movements or subsidence. Measurements are difficult, as high accuracy is needed. These data suggest that sea level is currently rising at about 1.5–3 mm yr^{-1} (CAZENAVE *et. al.,* 1999; NEREM, 1999). Since the satellite was only launched in 1992, the long-term accuracy of this technique is not yet well established, as a long record is required for robust trends to be estimated. The main confounding factor is the El Niño-Southern Oscillation (ENSO) effect, an oscillation in the sea surface temperatures (and other oceanic and atmospheric variables) of the Pacific Ocean that has an irregular period of about 2–7 years (see for example ALLAN *et al.,* 1996). It causes substantial variations in global average sea level every few years (NEREM *et al.,* 1999), and these affect the TOPEX/POSEIDON data recorded since 1992, as ENSO has been predominantly in a negative phase since this time. There is also some regional variation of sea level rise in the satellite data, which may reflect real variations from location to location (CHURCH *et al.,* 2001; LAMBECK, 2002).

The TOPEX/Poseidon data indicate a recent sea level rise that is faster than the mean rate estimated for the 20th century. CHURCH *et al.* (2001) were unable to ascribe the reason for the difference, attributing it either to a recent acceleration in sea level rise, systematic differences between satellite and tide-gauge measurements, or the shortness of the satellite record. GREGORY *et al.* (2001) point out that there is currently no discernible acceleration in the long tide gauge record. However, the detection of any significant acceleration is difficult with the present sparse geographical coverage of long gauge records.

Components of Observed Sea Level Rise

Thermal Expansion

Thermal expansion is the most important component of global sea level rise. In principle, the size of this component over the 20th century can be calculated from changes in oceanic temperature and salinity. Measurements are difficult, however, and complicated by the relative paucity of observations in the oceans. Nevertheless, comparison of regional and global observations suggests that thermal expansion has been proceeding at a rate of about 1 mm yr^{-1} over the past several decades (LEVITUS *et al.,* 2000; CHURCH *et al.,* 2001).

This is similar to the estimates of this quantity made by numerical models of the ocean over the same time period. These models range in complexity from simple upwelling/diffusion energy-balance climate models such as those of WIGLEY and RAPER (1987, 1993) and RAPER *et al.* (1996) to complex global ocean three-dimensional general circulation models (GCMs, also known as global climate models). A GCM solves equations that represent the fundamental aspects of the climate system, such as temperature, rainfall, winds and so on. Because of their complexity, GCMs are typically run on the largest and fastest supercomputers available. GREGORY *et al.* (2001) give a comparison of thermal expansion as simulated by a number of GCMs. These models display variability on decadal time scales that also occurs in the real ocean. This variability makes the analysis of trends more difficult, as decadal variations tend to obscure genuine long-term trends in the data, such as those associated with climate change.

Other simpler models include the two-dimensional model of DE WOLDE (1995, 1997) and the subduction model of CHURCH *et al.* (1991), subsequently developed by JACKETT *et al.* (2000). The major advantage of the simple models is that, because of their low cost, they can be easily modified and run for many different greenhouse-gas emission scenarios. Their main disadvantage is that they do not entirely realistically represent the processes involved in the penetration and distribution of heat into the ocean, and they have to be calibrated against GCM results. Additionally, they only give a global mean estimate and do not give any information on regional variations in sea level rise.

Based on observations and various model estimates, the contribution of thermal expansion to global sea level rise over the period 1910–1990 has been estimated at between 3–7 cm.

Glaciers and Ice Caps

It is clear that the vast majority of the world glaciers and small ice caps have been retreating in the past century, thereby contributing to global sea level rise. Nevertheless, it is difficult to calculate precisely their contribution. There are about 100,000 glaciers in various parts of the world with differing sizes, rates of melting and movement. Precise measurements of the "mass balance", or the net gain or loss of water by the glaciers, have only been made for a few of these. Instead, global estimates are made by dividing the glaciers into several main regions and estimating the mass balance for each region by assuming that the glaciers in each region all have the same mass balance as the specific known mass balance of a "typical" glacier in that region (KUHN *et al.,* 1999). There are also few observations of glaciers in regions that are considered important sources of meltwater, for example, the coasts of Alaska and Patagonia. Estimates that have been made (*e.g.* MEIER, 1984; MEIER, 1993; DYUGEROV and MEIER, 1997; GREGORY and OERLEMANS, 1998; COGLEY and ADAMS, 1998) suggest that glaciers and ice caps have contributed about 2–4 cm to global sea level rise over the period 1910–1990.

The Greenland and Antarctic Ice Sheets

The great ice sheets covering most of Greenland and Antarctica are governed by slower processes than those of smaller glaciers and ice caps. The complex dynamics of ice flow and interactions with the surrounding rock and sea make the process of estimating the contribution of these areas to global sea level rise a difficult task. Note that there are also extensive floating ice shelves, and in the past these have been affected by changes in temperature; for example, the break-up of the small Larsen Ice Shelf in Antarctica has been attributed to such temperature increases (ROTT *et al.,* 1995). Because these ice shelves are already floating, however, even if they melted completely, they would have no effect on sea level. It is the grounded ice (the ice resting on bedrock) on the continents of Antarctica and Greenland that has the potential to affect sea level. Together, these ice sheets contain enough water to raise the sea level by about 70 meters if they were to melt entirely (CHURCH *et al.,* 2001).

The large ice sheets gain mass by accumulation of snow, and lose it by melting, evaporation/sublimation, wind-driven snow drift and ice flow into the surrounding oceans. Since the response time for changes in ice flow is about 100–10,000 years (HUYBRECHTS and DE WOLDE, 1999), it is likely that the ice sheets are still adjusting to past melting and accumulation changes, particularly those associated with the end of the last Ice Age. In Antarctica, the low average surface temperatures imply that little surface melting occurs and ice loss is mainly by iceberg calving. In Greenland, by contrast, temperatures are higher, so melting and runoff are more important processes in the total mass balance (*e.g.* SMITH, 1999), and thus the response is quicker.

There is a contribution to the sea level rise that has occurred in the past century that is related to the slow adjustment of the ice sheets. This is because past changes in accumulation and melting rates take a long time to be reflected in changes in the rate of ice flow across the "grounding line", the line of contact between rock, sea and ice. The total mass balance of the grounded ice sheet is given by

$$\frac{dV}{dt} = Q_a - Q_m - Q_b - Q_g \qquad (1)$$

where Q_a is the annual net surface accumulation, the balance between snowfall, evaporation/sublimation and drifting snow; Q_m is the loss by surface melt; Q_b is the non-surface melting of the ice sheet; and Q_g is the movement of ice into the ocean, either through iceberg calving or flow across the grounding line.

The most accurate estimates of the long-term ice sheet contribution are made by combining model results (*e.g.* HUYBRECHTS and DE WOLDE, 1999) with evidence of sea level changes over the past several thousand years contained in the geological record. This comparison suggests an ongoing contribution of 0–5 cm from this effect during the 20th century.

The observed changes in temperature and precipitation in the 20th century would cause short-term changes in the mass balance of the ice sheets, which must be evaluated separately from the long-term contribution calculated above. Using the ice sheet model of HUYBRECHTS and DE WOLDE (1999), CHURCH *et al.* (2001) estimate that the contribution of Antarctica to global sea level over the past 100 years is between −2 and 0 cm, with the negative sign caused by increased accumulation of snow. The contribution of Greenland over the same time period is estimated as 0 to 1 cm.

Surface and Ground Water Storage

This term represents the changes in the quantity of liquid stored in the ground and in lakes and reservoirs, as well as the effect of changes in land use on runoff and evaporation. The contributions to sea level rise from these effects can be both positive and negative. Positive contributions could come from increased extraction of ground water and loss of wetlands, as these processes would increase the net water flow into the oceans. Negative contributions could come from surface reservoir and lake storage, and irrigation (GORNITZ *et al.,* 1997; SAHAGIAN, 2000).

Unfortunately, modeling of changes in hydrologic practices due to climate trends is in its infancy, and there are wide ranges of estimates of most of these terms. Current knowledge suggests that the net contribution from these effects to the total sea level rise could be important. GORNITZ *et al.* (1997) suggest an increasing storage of water on land and suggest the current rate could be as large as −1.2 to −0.5 mm yr^{-1}, with a central estimate of −0.8 mm yr^{-1}. On the other hand, VÖRÖSMARTY and SAHAGIAN (2000) give a much smaller value (and with the opposite sign), 0.06 mm yr^{-1} for the rate averaged over the 20th century. This leads to a large range of the estimated contribution of this component to sea level in the 20th century. CHURCH *et al.* (2001) give a rate of −1.1 mm/yr to +0.4 mm/yr for the period 1910–1990.

Thawing of permafrost gives a positive contribution to sea level rise in the 20th century (ANISIMOV and NELSON, 1997) of 0–0.5 cm over the period 1910–1990 (CHURCH *et al.,* 2001).

Isostatic and Long-term Glacial Effects

In many parts of the world, land is still rebounding from the weight of the great ice sheets of the last Ice Age (for instance, Scandinavia; LAMBECK *et al.,* 1998). Comprehensive models of these effects have been developed (*e.g.* LAMBECK and JOHNSTON, 1998; PELTIER, 1998). In addition, many measurements of variables related to sea level have shown that sea level has varied with changes in ice volume during and since the last glacial period (SHACKLETON, 1987; YOKOYAMA *et al.,* 2000). Local isostatic effects can be very large, larger than the rate of global average sea level rise caused by global warming, and need to be assessed for the region under consideration.

Table 1. *Estimated contributions to sea level rise over the twentieth century (in cm). After Church et al., (2001).*

Component	Low	Middle	High
Thermal expansion	3	5	7
Glaciers/small ice caps	2	3	4
Surface water and ground water (terrestrial) storage (not climate change)	−11	−3.5	4
Greenland ice sheet (20th century)	0	0.5	1
Antarctic ice sheet (20th century)	−2	−1	0
Ice sheets—adjustment since last Ice Age	0	2.5	5
Other	0	0.3	0.5
Total	−8	7	22
Observed	10	15	20

Tectonic Land Movements and Local Effects

Changes in land height due to tectonic effects can be large in some locations: for example, the Huon Peninsula of Papua New Guinea, where uplift has averaged between 2 and 4 mm yr^{-1} (CHAPPELL *et al.,* 1996), and parts of the Mediterranean, were similar rates of uplift have occurred (STIROS *et al.,* 1994). These rates are large enough to reduce substantially or even negate completely the local impact of sea level rise.

In some locations, subsidence of land is important, for instance in river deltas (STANLEY, 1997). Man-made subsidence of land caused by groundwater extraction can be large in some locations (*e.g.* Bangkok; BIRD, 1993). These would have to be estimated very locally, as they may differ substantially even within the boundaries of a municipality. Other local changes in the relative level of sea and land are caused by the extraction of oil and gas reserves (BIRD, 2000).

Summary

The contributions of the various components to observed sea level rise during the 20th century are summarized in Table 1. The results in this table are for the observed global mean warming of 0.45°C ± 0.15°C at the surface of the Earth over this time period. The estimates for the thermal component are based on simple models, while the glacier component is based on a combination of observations and models. Each component is associated with a range of uncertainty that is given by low and high bounds. The "total" amount of sea level rise referred to in Table 1 means the sum of all of the estimates of each component, while the "observed" amount is estimated from tide gauge records.

Obviously, a better determination of the components of the terrestrial storage term is needed. CHURCH *et al.* (2001) state that the quoted range for this term requires that several of its components lie simultaneously at the extremes of their ranges, which seems unlikely.

Table 2. *Total predicted global mean sea level rise for 2040 and 2100 (in cm).*

	Low	Mid	High
2040	3	12	30
2100	9	48	88

Future Global Sea Level Rise

The main tools used for estimating the future global and regional temperature changes needed to estimate sea level rise are climate models, usually GCMs. These models contain many interactions and approximations, some of which are not well understood. Nevertheless, they are the best available tools for the prediction of climate change, and their skill at representing the climate system continues to improve. A detailed description of the many current issues involved in climate modeling is contained in IPCC (2001). GCMs are used to estimate the response of the Earth's global mean surface temperature to changes in greenhouse gases, known as the *climate sensitivity.* Presently, there is a range of estimates of this quantity; this range represents a significant source of uncertainty in projections of future sea level change.

A range of projections of sea level in the 21st century can be made, depending on assumptions regarding the future concentration of greenhouse gases and the actual sensitivity of the climate system to increases in these concentrations. Table 2 summarizes the predicted contributions from the various components of sea level rise for 2040 and 2100, as given by CHURCH *et al.* (2001).

The values for 2040 are calculated using the upper and lower limits of the GCM response for the climate-change related components of sea level rise. Note that these projections do not include a contribution from future changes in terrestrial storage. Future thermal expansion has been estimated using a number of GCMs (GREGORY *et al.,* 2001). These models differ both in terms of their climate sensitivity and the ability of their ocean components to absorb heat. Thus a range of 21st century projections of this component are calculated.

Sensitivity of the ice sheets to climate change has been estimated by multiple regression analysis, simple models and GCMs. For Greenland, the consensus is that higher temperatures would cause sea level to rise, given that surface melting of the ice there is likely to accelerate with global warming (WARRICK *et al.,* 1996; THOMPSON and POLLARD, 1997; SMITH, 1999; JANSSENS and HUYBRECHTS, 2000; WILD and OHMURA, 2000). For Antarctica, where significant melting is unlikely to occur because of the much lower temperatures typical of this continent, it is considered likely that increased temperatures may lead to increased snowfall over Antarctica over the next century, thus contributing to a sea level fall. For example, WILD and OHMURA (2000) suggest a value of -0.48 mm $\text{yr}^{-1}{}^{\circ}\text{C}^{-1}$.

An important point to note is that there is little sensitivity before about 2050 to different assumptions regarding the amount of greenhouse gases emitted into the atmosphere. In other words, for the range of greenhouse gas emission scenarios considered, the rate of sea level rise would be relatively unaffected until after about 2050. This is because the ocean is still warming up as a result of the greenhouse gases that have already been put into the atmosphere. Uncertainties in future emissions of greenhouse gases play a smaller part than model uncertainties over the next few decades, as the ocean has a substantial thermal inertia and responds only slowly to external forcing by greenhouse gases. For example, by 2050, CHURCH *et al.* (2001) suggest that the uncertainties due to emissions alone are only a few centimetres of total sea level. The effects of differing emission scenarios become larger towards 2100 and beyond.

Impact of Interannual and Decadal Variability on Sea Level

Interannual (year-to-year) variability of sea level is substantial in many parts of the world in the current climate. For example, in the South Pacific region, differences in mean sea level between El Niño and La Niña conditions are more than 30 cm in a number of Pacific locations (*e.g.* MERRIFIELD *et al.,* 1999; BELL *et al.,* 1999). It is likely that these variations will continue in the future (MEEHL and WASHINGTON, 1996; KNUTSON *et al.,* 1997; TIMMERMAN *et al.,* 1999). Nevertheless, projections of the effect of climate change on ENSO have considerable uncertainty. In constructing a scenario of future sea level change in regions where interannual variability is large, these variations must be taken into account. For future sea level conditions in these regions, the best current estimates might be made by simply assuming the same magnitude of interannual variation observed in the current climate and add these to the projections of global mean sea level rise given above.

Recent evidence has been found of decadal (longer than 10 years) variability in Pacific region sea level (BELL *et al.,* 1999; STURGES and HONG, 2001). This may need to be taken into account in the construction of the sea level rise scenarios in some regions. Decadal variability is an active area of research and its causes are not yet fully understood (*e.g.* CANE and EVANS, 2000).

Possible Collapse of the West Antarctic Ice Sheet (WAIS)

A more drastic sea level rise scenario involves the hypothesis that the western portion of the Antarctic ice cap is inherently unstable. This portion of the ice cap rests on bedrock that is below sea level over much of its area. Concern has been expressed that the west Antarctic ice sheet (WAIS) is vulnerable to changes in sea temperature, and there is a risk that it will discharge into the sea at greatly increased rates some time in the future. WARRICK *et al.* (1996) concluded that it was not possible even to estimate the likelihood of this occurring, as scientific results were not conclusive, with some authors suggesting that drastic rates of discharge were possible, while others suggested that they were not. BENTLEY (1997) argued that increased rates of discharge from the WAIS could only occur if a natural collapse was imminent, as the impact of climate change was unlikely to trigger it, for various reasons. Given the geological record, he estimated the probability of this occurring within the next century of about

0.1%. Even then, he considered that a "collapse" would only involve roughly a doubling of the expected rate of sea level rise rather than the rapid, massive slide of the ice sheet into the sea envisaged in some popular literature. CHURCH *et al.* (2001) conclude that based on our current understanding of the WAIS, a collapse was very unlikely in the 21st century. A panel of experts concluded that there is a 98% chance that a collapse will not occur this century, where a collapse is defined as a contribution from the WAIS to global sea level of at least 10 mm yr^{-1} (VAUGHAN and SPOUGE, 2002).

GCM Simulations of Regional Variations of Sea Level Rise

It is likely that there will be regional variation of sea level rise due to changes in ocean circulation as a result of global warming. Changed wind patterns will also change currents. These changes may be estimated using coupled ocean-atmosphere GCMs, but the results of various models currently differ considerably (*e.g.* GREGORY, 1993; CUBASCH *et al.,* 1994; BRYAN, 1996; JACKETT *et al.,* 2000; GREGORY and LOWE, 2000). GREGORY *et al.* (2001) show that projected sea level change is far from uniform spatially. Model results give some locations with sea level rise of more than twice the global average, while other regions show a sea level fall. Patterns simulated by the various models generally are not similar, but a few common features are seen. These include a minimum of sea level rise in the Southern Ocean south of 60°S and a maximum in the Arctic Ocean. In general, though, there is little consensus on the details of the regional distribution of sea level rise.

PLANNING FOR SEA LEVEL RISE

From Science to Planning

While the scientific evidence for future sea level rise seems convincing, the estimates of future sea level rise produced by (for example) WARRICK *et al.* (1996) or CHURCH *et al.* (2001) are not completely sufficient for planning purposes. The range of estimates is large, partly because of uncertainties in the current scientific knowledge of this issue, and partly because of different estimates of future greenhouse gas emissions. Planners would ideally like a projection of a particular sea level rise to be associated with a certain probability. It is not useful for planners if the entire range of predicted sea level rise is assumed to be equally probable. In any event, this cannot be the case, since the range is due to a combination of component ranges of uncertainty, and thus the extremes of this range must be less probable than the central estimate (JONES, 2001). Many of the GCM simulations reported in the current IPCC (2001) report have employed assumptions regarding the future emissions of greenhouse gases based upon the Special Report on Emissions Scenarios (SRES; NAKICENOVIC *et al.,* 1999). These various scenarios are constructed using very different postulated future world economic and social conditions to arrive at a selection of "storylines". When these storylines were constructed, it was explicitly stated that no probabilities could be attached to any of them; in other words, that no statement could be made regarding the likelihood of future world conditions actually resembling any of the storylines. One could not even assume that the story lines were equally probable.

For planners, this causes a difficult situation, as the projections of future climate made by GCMs using the SRES scenarios differ considerably between storylines by the end of the 21st century. The questioning of assigning probabilities to future global warming is now the subject of lively debate (*e.g.* PITTOCK *et al.,* 2001). Nevertheless, before 2050, this is not a significant issue, as the sea level rise projections before about this date are not strongly affected by differing emissions scenarios, a result of the large thermal inertia of the oceans and other components of the climate system. As mentioned earlier, the main source of uncertainty before 2050 is due to uncertainty about the science of sea level rise, not the future emissions of greenhouse gases.

What amount of sea level rise should therefore be assumed for planning purposes? The best approach might be through a risk assessment, based upon the estimated probability of various levels of sea level rise (*e.g.* JONES, 2001). Risk assessment aims to produce meaningful outcomes under conditions of high uncertainty. For sea level rise, risk assessment has taken two forms: as a probability distribution for a single outcome (*e.g.* the 95th or 99th percentile), or the calculation of the probability of exceedance above a given threshold identified as a hazard. TITUS and NARAYANAN (1996) concluded that a sea level rise of between 10 and 65 cm by 2100 had an 80% probability of occurring, while the 99th percentile was associated with a 104 cm rise. Alternatively, JONES (2001) suggests the use of critical thresholds, a concept that links an unacceptable level of harm with a key climatic or climate-related variable. For coastal impacts, the critical threshold is then linked to a projected range of sea level scenarios, through key climatic and marine variables, and the risk of exceedance of the threshold is calculated. JONES (2001) gives an example based on the joint probabilities of exceedance of a sea level threshold and the influence of atmospheric CO_2 on coral reef carbonate growth. For all types of risk assessment, the scenario-building exercise should incorporate all ranges of uncertainty that can be quantified, whether by expert analysis, dynamic modeling or statistical methods (usually a combination is applied).

One method would involve combining a probability distribution of sea level rise with detailed information on the vulnerability of infrastructure such as buildings (ABBS *et al.,* 2000), leading to a cost-benefit analysis of the cost of regulation versus the benefits of reducing damage. This is a complicated procedure, requiring as it does excellent land elevation data and good knowledge of the value of infrastructure under threat. Local probabilities for sea level rise were estimated for the United States by TITUS and NARAYANAN (1995). They provided a methodology for combining projections of future global sea level with local changes in sea level due to land subsidence and other factors detailed above.

While this approach is desirable, simpler interim solutions have been adopted. For example, BETTS (1999) devised a planning scheme for sea level rise in the City of the Gold Coast in Australia. This was based upon projections of sea level rise by 2050 for the Gold Coast made by WALSH *et al.*

(1998), which were estimated from the following components: the predicted global mean sea level rise contained in WARRICK *et al.* (1996), of 10–40 cm; the hydro-isostatic effect in the Gold Coast region, −2 cm; and an uncertainty factor which allows for possible geographic variations in sea level rise, −5 to + 20 cm, reflecting possible regional deviation from the global mean sea level rise. This gives a total of 3–58 cm, with a central estimate of 18 cm. This range remains consistent with the later sea level estimates of CHURCH *et al.* (2001) detailed in Section 2. Tectonic effects and interannual variations caused by ENSO are small in the Gold Coast region. Possible large effects caused by land subsidence were not explicitly considered in the planning guidelines, as these would have to be estimated very locally. The regional variation estimate could be improved by using spatial patterns of sea level rise similar to those recently produced by GREGORY *et al.* (2001).

BETTS (1999) assumed that the central estimate of sea level rise thus calculated (18 cm by 2050) was not conservative enough for use in planning, as almost by definition the central estimate would have a 50% chance of being an underestimate. Thus a slightly higher sea level rise allowance was made. BETTS (1999) assumed a sea level rise of 30 cm by 2050 (subsequently modified to 27 cm, this being the central estimate for 2070 estimated by WALSH *et al.,* 1998; BETTS, 2001). This planned allowance for sea level rise is on top of an existing 30 cm freeboard allowance above the 1 in 100 year flood level, the planning approach used in the current climate. Ideally, however, a risk assessment based upon a probability distribution of sea level rise would be a preferred method. Note, though, that sea level will continue to rise well past 2100 for all but the most stringent emissions scenarios (see CHURCH *et al.,* 2001 for details).

An increase of sea level would restrict the outflow of flood waters from local river systems into the ocean, thereby increasing peak flood levels. Damage estimates in the region are very sensitive to increases in flood levels. The estimated flood damage in a portion of the Gold Coast region has a very non-linear increase in damage with flood height. Higher sea levels and storm-generated wave set-up could also cause changes or even breaches in low dune systems, although riverine runoff poses the greatest flood risk in this region (MCINNES *et al.,* 2002a) and the incidence of such flooding may not be strongly influenced by sea level rise. In some locations, the interaction between river flooding and sea level rise has the potential to raise flood levels substantially in a number of locations (*e.g.* ARNELL, 1999; NICHOLLS *et al.,* 1995).

As mentioned earlier, the life of assets such as dwellings is long enough potentially to be affected by climate change. For the purpose of the Gold Coast planning scheme, an average life of assets of 50 years was adopted, but building platform levels were required to remain above peak flood levels 70 years hence. Other long-lived infrastructure, such as main roads, bridges, ports and harbours, may also be affected on these time scales.

Impact of Sea Level Rise on Storm Surges

Although not explicitly considered in this paper, the climatology of storm surge events will be affected by sea level rise in vulnerable locations. To incorporate sea level rise into estimates of storm surge return periods, it is usually adequate simply to add the sea level rise linearly to the storm surge height (*e.g.* ABBS *et al.,* 2000; MCINNES *et al.,* 2002b). The effects of climate change may also included regional changes in storm frequency and intensity, which may affect the storm surge return periods in particular locations (IPCC, 2001). The vulnerability to storm surge needs to be estimated at specific locations, as it depends on the details of geography and ocean depth at a particular location. For example, MCINNES *et al.* (2002b) found that the increase in the 100-year storm surge height due to storm intensity changes is greater than the contribution due to sea level rise at a location on the northeastern Australian coast. In particular, increases in intensities of tropical cyclones are now considered “likely, in some locations” (IPCC, 2001), which would have effects on the storm surge climatology in some Australian locations. Increases in mean sea level will exacerbate flooding in regions already vulnerable to storm surge.

Impacts and Practical Planning

There is a substantial literature on practical planning for sea level rise (*e.g.* BILJLSMA *et al.,* 1996; IPCC CZMS, 1990; KLEIN *et al.,* 1999; TITUS, 1998; NICHOLLS *et al.,* 1999; NICHOLLS and MIMURA, 1998). Sea level rise itself does not cause coastline recession; it is the resulting changes in the wave climate and alongshore transport that causes increased erosion (*e.g.* LEATHERMAN, 2001). For beaches, the rate of lateral beach erosion is typically two orders of magnitude greater than the increase in sea level (LEATHERMAN, 2001). This relationship was first enunciated by BRUUN (1962) and is known as Bruun’s rule. Although this model is highly simplified compared with real beach processes, it forms the basis of a number of planning strategies for sea level rise in Australia and elsewhere.

Responses to sea level rise can be classified into a series of human adjustments that can be used to identify potential effects on beach and dune resources (NORDSTROM, 2000). TITUS (1990) gives the following classification system for management strategies:

(1) accommodation/no protection;
(2) protection (*e.g.* levee or sea wall);
(3) adaptation (*e.g.* island raising);
(4) retreat.

For urban areas, accommodation or abandonment is generally not a viable option, as the cost of the infrastructure to be abandoned is often too high. An exception is low-lying urban regions containing little infrastructure *e.g.* wetlands.

Protection has the advantage is that it does not require major institutional changes regarding land use. For example, a beach could still be maintained by artificial nourishment, the placing on the beach of sand obtained elsewhere. This strategy is costly and depends upon a ready supply of sand, which may not be available for all locations. On the east coast of the USA, the cost is around US$10,000 per beachfront lot per year (PILKEY and HUME, 2001). Because of the cost of this process and the limited supply of sand for nourishment,

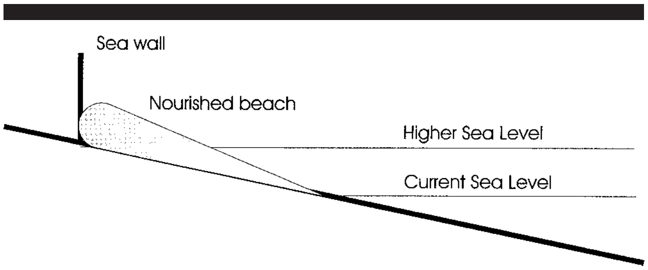

Figure 1. Schematic diagram of response to higher sea level, including a sea wall and a nourished beach.

urban planners could be faced with some hard choices regarding the future of urban beaches in regions where the mean sea level is rising.

Alternatively, sea wall construction costs are estimated at about US$3000 (1998 dollars) per linear metre, with maintenance costs of 4–10% per annum, depending on exposure to wave action (NEUMANN and LIVESAY, 2001). For aesthetic and amenity reasons, in vulnerable urban areas, a combination of sea wall construction and beach nourishment may be necessary (see Figure 1). Timelines for the construction of protection works need to be carefully considered. YOHE *et al.* (1999) pointed out that postponing protection works until the decade when they are needed could save costs of an order of magnitude. Strategies to deal with sea level rise must be local because of the very heterogeneous nature of the coastline (NEUMANN and LIVESAY, 2001). Sea walls in tourism areas may well protect beach-front infrastructure but reduce the attractiveness and viability of the area as a resort.

Island raising involves putting sand on the beach, as well as raising the nearby buildings and support infrastructure. Advantages of this strategy include that no one is prohibited from building or rebuilding, and the government does not have to buy property (TITUS, 1990). Disadvantages include the cost and environmental problems in dredged areas from which the sand and fill material would have to be extracted.

Engineered retreat mimics natural retreat by artificially filling the bay sides of barrier islands while the ocean side erodes, a strategy recommended for barrier islands off the coast of the United States. A regulatory strategy that could encourage an efficient private response to sea level rise involves a system of rolling easements, whereby development is prohibited progressively further inland as time goes on (TITUS, 1998).

Alternative descriptions of these management strategies have been proposed. KAY *et al.* (1996) prefers the nomenclature used in natural hazard research:

—event protection
  ○ hard: sea walls
  ○ soft: beach nourishment
—damage prevention
  ○ avoidance—prevent development
  ○ mitigation—building codes, flood-proofing
—loss distribution
  ○ individual—insurance
  ○ community—insurance/relief/cost sharing
—risk acceptance
  ○ includes doing nothing

As already mentioned, sea level rise *per se* does not cause geomorphic change: extreme wave activity does. Thus it is possible that in some locations beaches may not recede despite relative sea level rise. In this context, BELL *et al.* (2001) examined the impact of climate change on the coastal margins of New Zealand. The prediction of shoreline response to climate change is complex, and beach response will depend upon factors such as sediment supply, wave climate, storm frequency and alongshore changes in sediment movement, not just on the amount of relative sea level rise. Wind and wave changes in particular could have a substantial effect, and much less work has been done to examine changes in these factors in a warmer world. Projected increases in storm rainfall intensities (*e.g.* CSIRO, 2001) could lead to increased sediment flow in some locations. For example, the Pegasus Bay shoreline response study (BELL *et al.,* 2001) showed that plausible changes in wave climate or sand supply could *reverse* the beach recession caused by sea level rise.

In summary, for developed urban areas in the long term, managed retreat may need to be considered, as other strategies will become increasingly expensive. In the medium term (decades), urban beaches will need beach re-nourishment and associated holding structures such as sea walls. Changes in storm and wave climatology are crucial factors for determining future coastal erosion.

Current Regulatory Environment in Australia and New Zealand Regarding Sea Level Rise

In planning for sea level rise, the scientific issues need to be put into the context of management decisions and the present regulatory regime that governs response options. For Australia, this topic was previously reviewed by KAY *et al.* (1996). Both New Zealand and Australian regulations are examined here, as until recently one of the major differences between the two countries was that New Zealand had a statutory regional planning process, whereas in Australia plans were mostly non-statutory i.e. did not have the force of law.

New Zealand

BELL *et al.* (2001) give a summary of the current regulatory environment in New Zealand. They surveyed local authorities to assess the degree to which current statutory plans have taken sea level rise into account. Quite a few local councils have specifically included sea level rise in plans. Mostly they use IPCC projections without regionally-varying relative sea level rise caused by other factors. A need was identified for improved and more accurate topography and coastline data to categorise local vulnerability better.

Australia

National: National guidelines on responding to the effects of climate change in coastal engineering design were published by the INSTITUTION OF ENGINEERS, AUSTRALIA (1991). More recently, INSTITUTION OF ENGINEERS (2000) identified marine climate change and its effect on the coastal zone as the most important research priority for coastal and ocean engineering in Australia.

As part of the National Local Government Coastal Management Policy of the Australian Local Government Association, the Intergovernmental Coastal Reference group has been established by State and Local governments across Australia to discuss matters relating to coastal policy as well as management. The National Oceans Office is a Commonwealth Executive Agency whose role is to coordinate the development of regional marine plans and the overall implementation and development of Australia's ocean policy. In the context of sea level rise, Australia's Oceans Policy recommends improved monitoring of sea level.

Victoria: In Victoria, overall strategic direction for planning and management of coastal areas is provided through the Victorian Coastal Strategy that is developed and endorsed by the State Government pursuant to the Coastal Management Act 1995. Both the 1997 Strategy and the recently released Victorian Coastal Strategy 2002 identify a requirement for coastal planning and management bodies to take a long-term approach to planning and decision making having regard to risk issues including changed climatic conditions and storm events. The Act requires that managers of coastal areas give effect to the Strategy.

The Strategy encourages a program of vulnerability assessment within a 100-year planning horizon as a basis for detailed statutory planning. The Victorian Coastal Strategy is specifically referenced in the State Planning Policy Framework and is required to be taken into account by planning authorities through planning schemes. A range of studies and modeling assessments are underway, as part of the Federal Government's Greenhouse Strategy and Coastal Strategy commitments, to develop improved estimates for detailed planning.

Regionally, several initiatives have been taken to encourage greater understanding and to improve planning predictions. A study is currently under way, focusing on the Gippsland Lakes region, to establish a consistent methodology for the calculation of the 1% flood probability in estuaries (TAN *et al.,* 2001). Once this methodology is established, it is anticipated that it will be widely applied elsewhere. If successful, this will enable a better delineation of estuarine vulnerability to sea level rise.

At the local level, guidelines for allowances for flooding are set by local municipalities and Catchment Management Authorities. A typical freeboard allowance in floor level heights would be 300 mm above the 1 in 100-year average recurrence interval of river or sea level, but this has not specifically included sea level rise. In terms of specific management initiatives at the local level, these have been limited. In Victoria, possible vulnerable urban areas include sections of the Port Phillip Bay coastline from Port Melbourne and Brighton and other parts of both the eastern and western shores, as well as towns in the Gippsland Lakes region such as Lakes Entrance (COASTAL INVESTIGATIONS UNIT, 1992; MCINNES and HUBBERT, 1996).

Tasmania: Tasmania's coastal policy is a statutory document and contains some recommendations about the need to take sea level rise into account in planning. These recommendations are quite general, however, and to date no real planning decisions have been made on the basis of them.

The Tasmanian State Coastal Policy (http://www.delm.tas.gov.au/env/coastpol.html) states that "policies will be developed to respond to the potential effects of climate change (including sea level rise) on use and development in the coastal zone." Other than the general direction set by the State Coastal Policy, the State Government does not currently offer guidance to planning authorities on considering climate change in the planning process. Approximately ten years ago, the Commissioner for Town and Country Planning advised Councils that they should consider the climate change implications to proposed coastal subdivisions. As a result, some councils did include this issue in their planning schemes and others considered it as part of the subdivision approval process. The replacement of the Commissioner by a Panel and now by the Resource Planning and Development Commission has seen this requirement decline in perceived importance. No specific planning advice or requirement has been provided to Councils by the Commission or State Government in recent years.

Tasmania has six Regional Coastal strategies; these are non-statutory documents and cannot directly affect the planning process. Twenty-three out of twenty-four coastal Councils are involved in these Strategies and where appropriate will amend planning schemes to reflect priority recommendations.

In 1995, Tasmania carried out a case study on South Arm in the Clarence municipality as part of the National Coastal Vulnerability Assessment Case Studies Project funded by the Federal Government. More recently, the whole coast of Tasmania has been assessed to identify and locate the type and extent of geomorphic types around Tasmania. Further work is being carried out to identify how this information can be used to analyse coastal vulnerability to climate change effects over the next century. A pilot project for part of the coast will occur this year (2002), but its extension around the entire coast will need to await further funding.

New South Wales: The NSW Government is currently undertaking a three-year comprehensive coastal assessment with the objective of identifying (for planning) those areas of the coast that may reasonably be developed. Areas of significant ecological, social or heritage values and those areas likely to experience significant future coastal hazard will be quarantined. In New South Wales, coastal management plans are prepared through local coastal management committees constituted by local government. These plans are jointly funded by State and local government and undergo a defined management process outlined in the NSW Coastline Management Manual. Definition of the coastal hazards takes into account the impact of sea level rise and future shoreline recession. This manual is currently being rewritten and will amalgamate both coastal and estuarine planning procedures for NSW. It will promote a risk-based approach to addressing coastal and estuarine hazards.

Changes to the NSW coastal legislation currently before the parliament will, amongst other things, require coastline management plans to be formally gazetted. In approving these plans the state government may ensure that sea level rise is appropriately considered.

The existing manual for preparation of coastal management plans in NSW (since 1990) has included guidelines requiring consideration of sea level rise in defining coastal hazard areas. Over recent years, consultants preparing studies for Councils have simply applied the Bruun rule to IPCC mid-range scenario projections. Generally, this has resulted in a recommended allowance of an additional setback of 10 m to 20 m over a 50-year planning horizon. Virtually all local coastal councils in the State have included such an allowance in the hazard definition studies upon which their management plans are subsequently based. For example, the city of Newcastle is currently developing a city-wide coastal management plan that includes broad consideration of sea level rise issues.

Queensland: The recently promulgated State Coastal Management Plan was scheduled for implementation in February 2002[1]. The State coastal plan describes how the coastal zone is to be managed as required by the Coastal Protection and Management Act 1995, and is a statutory document. The State plan states that coastal management plans must address the potential impacts of climate change through management approaches along the lines of those mentioned in section 3.2. Regional coastal plans are to operate in combination with the State Coastal Plan.

The Plan states: "Planning for the coast must address the potential impacts of climate change through the following hierarchy of approaches:

- avoid—focus on locating new development in areas not vulnerable to the impacts of climate change;
- planned retreat—focus on systematic abandonment of land, ecosystems and structures in vulnerable areas;
- accommodate—focus on continued occupation of near-coastal areas but with adjustments such as altered building design; and
- protect—focus on the defence of vulnerable areas, population centres, economic activities and coastal resources."

It further states: "Where areas vulnerable to stormtide inundation have been developed, further development in these areas needs to address vulnerability to sea level rise and storm tide inundation".

Since the State plan has only recently been promulgated with statutory authority, to date the local planning in Queensland for sea level rise has varied considerably. Recent local planning for sea level rise includes that of the Gold Coast City Council, discussed in section 3.1.

South Australia: There is a long history of allowance for sea level rise in local planning in South Australia (SOUTH AUSTRALIAN COAST PROTECTION BOARD, 1992). Current provisions for sea level rise in development plans around the state allow for sea level rise of 300 mm over 50 years, plus the capability of being protected against further sea level rise of 0.7 meters, using protective measures such as sea walls and setbacks. All local council development plans incorporate sea level rise in their planning schemes.

Western Australia: The recently released draft State Coastal Statement of Planning Policy (coastal SPP) is a policy that must be taken into account by decision makers in coastal planning. The coastal SPP will guide development of coastal regional strategies, local planning strategies, and regional and town planning schemes. The SPP includes a schedule on the calculation of setbacks to ensure that development is setback from coastal processes as well as taking into consideration natural attributes such as wetlands and conservation of biodiversity, and recreational needs. The calculation of coastal processes is a three-part process, including calculation of three components: the trend of erosion or accretion; the incidence of extreme storm events; and the magnitude of sea level rise. The sea level rise component has been derived from IPCC (2001) and is taken to be 38 cm, translating into 38 m by the Bruun rule. The three calculated components are added to provide the setback for coastal processes and then the site-specific attributes and recreational needs are also considered to determine the total setback for development from the coast. It is likely that the setbacks may become incorporated into statutory planning through regional and town planning schemes in coastal areas where development pressures are most keen. Note that most of the WA coastal foreshores (more than 97%) are in some form of government ownership and hence the need to protect private coastal development is very limited in this State.

Summary

In summary, not all local councils in Australia have included sea level rise in their planning schemes. The recent adoption of statutory planning schemes in a number of States indicates a change in the local planning environment, however.

DISCUSSION AND CONCLUSION

In this paper, the latest estimates of both global mean and regional sea level changes in the 20th and 21st centuries are reviewed. In many locations, regional and local effects of sea level rise or fall need to be incorporated to make site-specific projections. Ideally, a risk management approach that combines the projected probability of sea level rise (the hazard) with the damage to the infrastructure affected (the vulnerability) could be used. JONES *et al.* (2004) offer a modified definition of these terms, where hazard is the critical threshold of damage, risk is the likelihood of the threshold being exceeded and vulnerability increases as the risk of damage increases. In the meantime, a number of simpler planning recommendations have been made. In general, the use of the central estimate (or most likely value) of sea level rise is insufficiently conservative for planning purposes, and higher values should be assumed. The impact of sea level rise on the ability of flood waters to escape into the open ocean and on storm surge return periods needs to be assessed for each location.

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[1] http://www.env.qld.gov.au/cgi-bin/w3-msql/environment/coast/management/msqlwelcome.html?page=sp.html

There has been a considerable amount of research focused on the issue of sea level rise itself. There has been rather less work on the possible changes in wind and wave climate in a warmer world, despite the fact that studies have shown that these, combined with changes in sediment transport, can accelerate or even reverse the shoreline recession caused by sea level rise. Climate change research priorities for coastal environment therefore should include changes in the wind and wave climate of the coastal environment, and changes in rainfall, which affects runoff and sediment deposition (INSTITUTION OF ENGINEERS, 2000). This is particularly important in locations currently vulnerable to storm surge.

The wide range of estimates of future sea level rise is still a problem for planning. The real issue for coastal planners should be the changes in the frequency of extreme sea level events and changes in wave climate; relatively small increases in mean sea level can cause substantial increases in extreme events. In addition, there appears to be substantial long-term variability in shoreline erosion, with erosion events perhaps related to decadal variations in the climate system such as the Pacific Decadal Oscillation (MANTUA *et al.,* 1997; BELL *et al.,* 1999).

It is clear that for highly developed urban coastal areas, protection options such as sea walls and beach nourishment will be employed to combat sea level rise for some time to come. Nevertheless, as the sea continues to rise, towards the end of this century these options will become increasingly expensive. It may be that some difficult choices will have to be made regarding whether protection continues for particular locations, or whether retreat and adaptation is employed instead (*e.g.* BELL *et al.,* 2001; LEATHERMAN, 2001).

The recent adoption of statutory coastal planning schemes in some States in Australia will probably lead to a change in local government planning responses to sea level rise, as not all local government authorities currently include sea level rise in their planning schemes. While this paper gives a broad overview of current planning for sea level rise in Australia, perhaps a survey is needed of current local government planning responses along the lines of that previously performed for New Zealand (BELL *et al.,* 2001). In addition, there is currently no Australian national program to fund coastal climate change impacts projects. This is limiting the response by local municipalities to sea level rise and other coastal climate change impacts.

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