J. KAU: Mar. Sci., **vol. 12,** *Special Issue,* pp. 3-11 (1421 A.H. / 2001 A.D.)

Marine Impacts of Potential Climate Change

D.T. Pugh, D.J. Dixon and P.L. Woodworth
[*]*Southampton Oceanography Centre,*
Empress Dock, Southampton SO14 3ZH,
[***]*Cleveland Villa, Illogan, Cornwall TR16 4DT,*
[***]*Centre for Coastal and Marine Sciences,*
Proudman Oceanographic Laboratory,
Bidston Observatory, Merseyside, CH43 7RA, UK

Abstract. The Intergovernmental Panel on Climate Change is now in an advanced stage in preparing its third scientific assessment, which will be published in January 2001. A number of marine impacts of climate change are anticipated in the next century, including changes in water temperatures, and perhaps ocean circulation patterns. However, the most direct change is likely to be an increase in global sea level. Popular concern about increased risks of coastal flooding in a future warmer world has led to extensive scientific investigation, new monitoring programmes and assessments of local vulnerability. Tide gauge measurements show an increase of around 20 cm over the past 100 years and plausible scenarios suggest further increases of 50 cm by 2100. The risks of coastal flooding will be significantly increasing. Changes in the intensity and pattern of storms may also influence risks of flooding. Until more extensive sea level records become available, including for example through new techniques such as satellite altimetry, these forecasts will probably not change substantially for some time. Now authorities with responsibility for coastal areas at risk must act to assess present risks and to put in place systems for giving an early warning of increasing future risks. This presentation will give some examples of measurements and studies to anticipate marine impacts, and will discuss recent measurements and studies in the Red Sea.

Introduction

The 1996 Report of the Intergovernmental Panel on Climate Change concluded, with proper scientific caution, that observations suggest "a discernible human influence on global climate". The Report also confirmed that global temperatures are likely to increase over the next century, as are average sea levels. Expectations of global warming due to the "enhanced greenhouse effect", although not universally accepted, are sufficiently well founded in observations and the potential consequences must be seriously considered. Relatively small investment now in observations and their interpretation can be seen as a reasonable insurance premium to ensure that possible impacts can be anticipated and planned for.

Marine impacts of climate change may include effect on coastal ecosystems and fisheries; flooding of infrastructure, habitation and amenities in low lying areas; loss of agricultural land through flooding and erosion; and damage to coral reefs. In this keynote presentation on marine impacts of potential climate change, related to the Red Sea and its environment, we will cover two aspects: Damage to coral reefs and increased risks of coastal flooding. The protection of the Red Sea environment is addressed in the Strategic Action Plan (PERSGA, 1998).

It is important to realise that all marine-related systems have some resilience to changing environmental conditions. Changes in sea level and sea temperatures over long periods can allow systems to adjust. However, the scale and in particular the rate of change which may result from enhanced greenhouse warming could place exceptional stresses on both natural systems and societal infrastructure.

Coral Reefs

There is increasing evidence that coral reefs are being damaged by unusual marine conditions. Coral "bleaching" of reefs around the Galapagos Islands has been associated with El-Niño warming of the Eastern Pacific upper ocean layers, including the near-surface layer in which corals grow. Small temperature increases above a normal maximum sea surface temperature of 27ºC can cause coral tissue to expel the zooxanthellae from the coral structure. Coral bleaching is the loss of the symbiotic algae that normally provides nutrients and energy to the colony of coral polyps. Although bleaching events are most commonly attributed to elevated water temperature, they can also occur in response to a range of other environmental stresses, such as reduced salinity or the presence of chemical contaminants (Harries, 1990).

Since the 1980's there have been increasingly frequent reports of coral bleaching events in many areas with particularly severe events in 1987 and 1990. The 1998 coral reef bleaching events were the most severe on modern record. An underlying trend of global warming may be the fundamental cause of the elevated sea temperatures that caused the severe coral bleaching. The long-term effects of this trend are uncertain, but it is becoming apparent that coral reefs may be particularly sensitive to the effects of climate change through both their response to temperature variation and to altered carbon dioxide levels.

The Indian Ocean appears to have been the most affected by the 1998 events (Wilkinson *et al.*, 1999) with many areas suffering over 70% mortality of corals. It has been suggested that many of these areas will take decades to recover, even assuming that environmental conditions are consistently favourable in the future. The sensitivity of Red Sea corals to climate change has been established (Dullo and Montaggioni, 1998 and Genin *et al.*, 1995). The majority of reefs in the Red Sea belong to the fringing type. They grow close to the mainland and are absent in wadi mouths because discharge events due to ephemeral precipitation may cause local, but serious damage of the reef-building assemblages. Coral barrier reefs and atolls also occur in the Red Sea, predominantly in the central and southern part. Genin *et al.* (1995) have shown a relationship between coral death in the Red Sea and the eruption of Mount Pinatubo. Cooler air temperatures encouraged deeper vertical mixing and an increased supply of nutrients to surface waters which fuelled extraordinarily large algal and phytoplankton blooms. Where these covered broad sections of the underlying reef there was extensive coral death. Isotopically light coral skeleton, indicating strong north east monsoon Red Sea inflow, correlates with periods of high Indian Ocean sea surface temperatures and with the predominantly negative (El Niño) phases of the southern oscillation.

For the Red Sea it is possible to conjecture that the potential strength and duration of wind systems with global warming could led to upwelling events along the south eastern Red Sea during the summer south west monsoon event, when winds along the entire Red Sea are from the north west. This could increase coral reef mortality with lowered water temperatures and conversely the increase in upwelled nutrients could increase local fisheries. The upwelling event along the south eastern coast of the Arabian Peninsula indicates the importance of such upwelling on productivity through increased chlorophyll concentrations and effects on fisheries and biota (Sheppard and Dixon, 1998).

The Global Ocean Observing System of the Intergovernmental Oceanographic Commission includes a Global Coral Reef Monitoring Network (GCRMN) linked to the International Coral Reef Initiative (ICRI, 1999). The GCRMN provides a framework and process to integrate efforts in assessing and monitoring the current status and future trends in coral reefs and their human use and values. It aims to link governments, scientists, resource managers and coral reef user communities to international and regional networks that collect, assemble and synthesise information on coral reef health in order to enhance awareness and effort to conserve and manage coral reefs for their sustainable use.

Coastal Flooding

The second (1996) scientific assessment of the Intergovernmental Panel on Climate Change suggests that average global air temperatures could rise by around 3ºC by the year 2100; it is plausible to suppose that this increase in global temperatures will in turn lead to a warming and expansion of the volume of ocean waters and the melting of some grounded ice, particularly of low-latitude glaciers. The resulting rise in mean sea level would have serious consequences for the risks of flooding of low-lying areas. These arguments have been well developed over the past few years, and form the basis of studies of projected global warming and sea level rise (Pugh and Maul, 1999). Sea levels vary over seconds, hours, days and decades. For each coastal location there is a distribution of probabilities for the sea level at any given time. For normal sea levels, natural and artificial systems give adequate protection. Only when there are extremely high sea levels, generated by high tides in combination with high storm surge activity, will there be risk of flooding. By definition the probabilities of these events is small but finite. In scenarios of climate change, it is the increase in these small, but finite probabilities which must be accommodated into coastal protection design strategies and systems. In assessing trends in flood risks it is useful to consider the separate trends in tides, meteorological effects and mean sea level. For the Red Sea, the seasonal cycle of mean sea level is particularly important. It will be seen below that each of these factors is important in the Red Sea.

Tides

For most coastal seas the main factor in sea level variability is tides, regular changes due to the gravitational effects of the Moon and Sun. These gravitational forces are extremely stable and predictable, and the response of the main ocean basins to these tidal forces can change very little over thousands of years (Cartwright, 1971); nevertheless, locally there have been significant changes in tidal amplitudes, particularly in shallow water or where artificial dredging has been used to improve access to ports.

The tides of the Red Sea are relatively small because of the narrow connection with the global ocean. Nevertheless, the semi-diurnal tides of the Red Sea are of interest because they are closely represented by a standing wave having a single central node (Defant, 1961). Careful analysis shows there is a progression of the wave in the expected anticlockwise sense around a central amphidrome (a point in the ocean with zero tidal amplitude) located near Jeddah. Because of its long narrow shape and steep sides the Red Sea has been used to test dynamical theories of tides, including early numerical solution of the hydrodynamic equations of motion. Figure 1 shows tidal ranges of less than a metre to the north and south of the Red Sea, with even smaller ranges at Jeddah. The tidal phases are opposite north and south of the Jeddah amphidrome. Red Sea tides are unlikely to change on the time scales considered here, but as Figure 1 shows, there are other strongly coherent variations of sea level over periods of around ten days which are of comparable amplitude.

Meteorological Effects

Several authors (Sultan *et al.*, 1995a&b; and Abdelrahman, 1997 & 1998 have described the relationships between sea level changes along the coast of Saudi Arabia and the local meteorology. Figure 2 shows the non-tidal variations in sea level together with local air pressures and winds at Jeddah over a period of 32 days. Figure 3 shows a longer period of sea level residuals, air pressures and along shore winds at Gizzan. Although there are some apparent correlations, there is no detailed correspondence immediately evident, particularly at higher frequencies. Nevertheless, Sultan *et al.* (1995a) showed from detailed cross-spectral analysis that variations of 3.5 day period are related to the along shore wind stress, while those of 2 and 4 day period are associated with the cross shore wind stress; cross-spectral analyses between the sea level changes show that low frequency variations between Port Sudan and Jeddah are coherent across the sea, while high frequency fluctuations are due to local meteorological conditions. The sea level response to atmospheric pressure changes is far from hydrostatic and at Port Sudan no correlation is found. At Gizan (Abdelrahman, 1997) monthly mean sea levels have been related to along shore wind stress and seasonal steric effects.

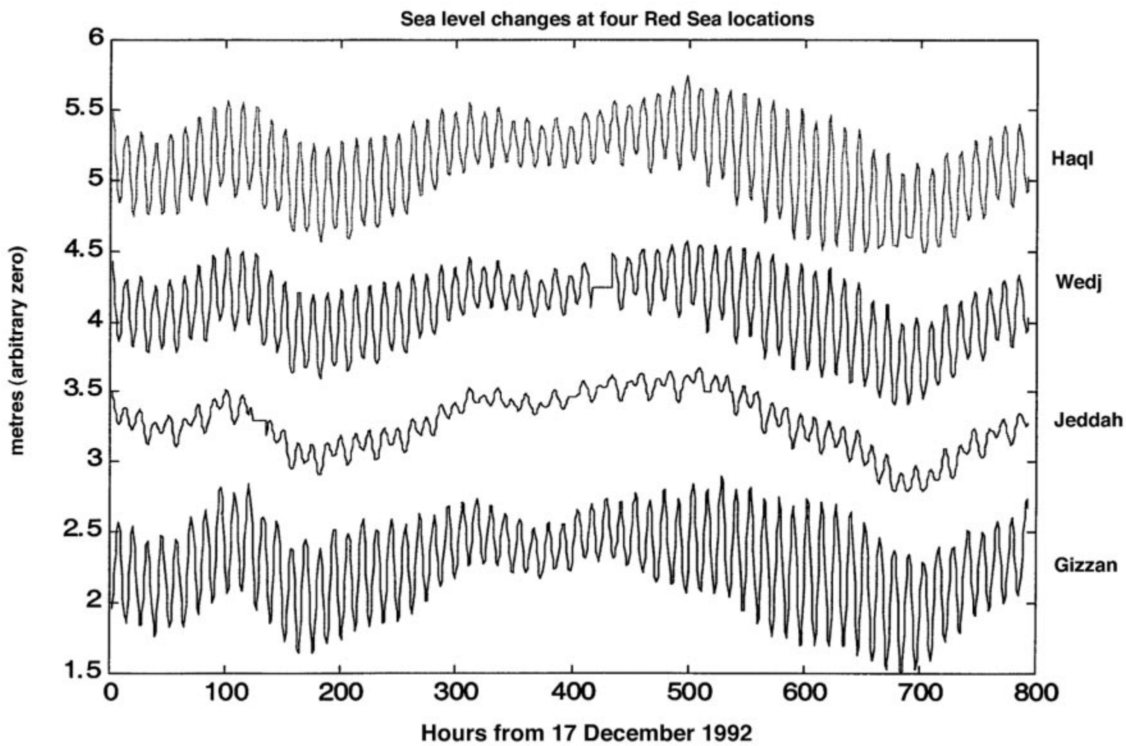

FIG. 1. Tidal variations at four Red Sea locations. The tidal range at Jeddah is very small because it is near the amphidrome for the semi-diurnal half-wave oscillation. The tides at Haql and Wedj north of the amphidrome are out of phase with those at Gizzan to the south. Note also the coherent low frequency variations over periods of weeks, which are not tidal.

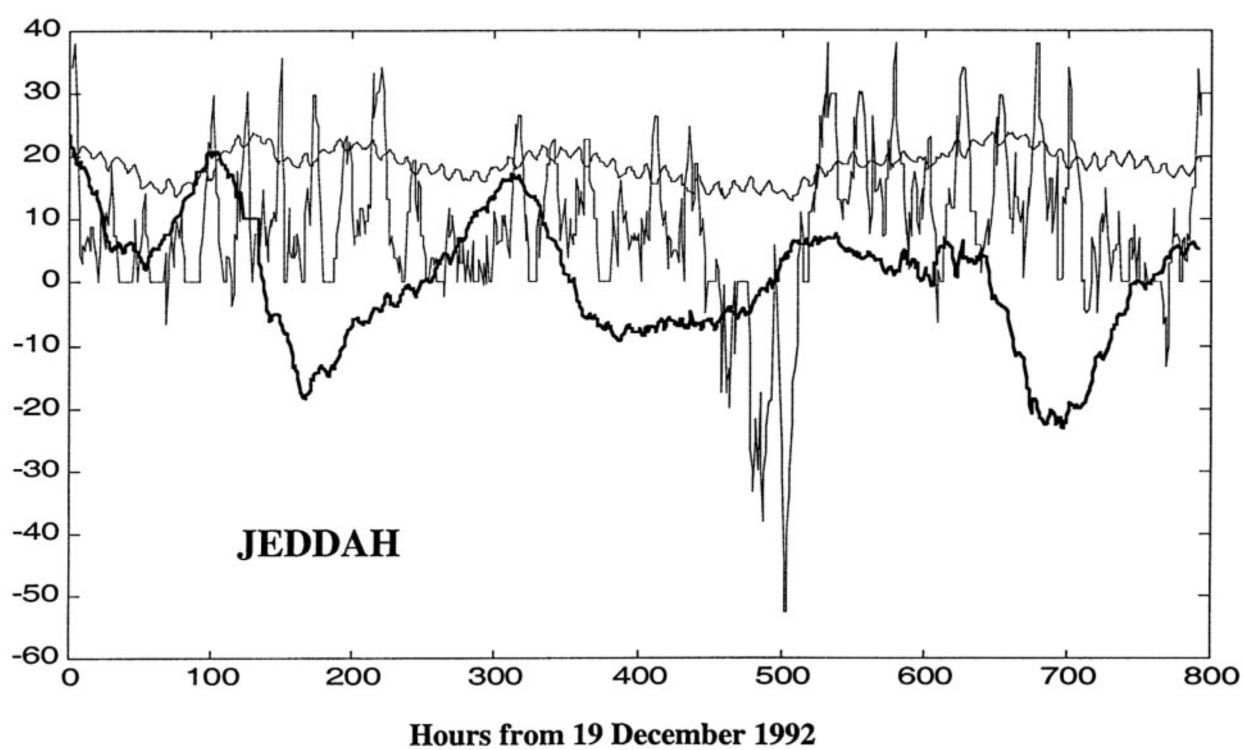

FIG. 2. Relationships between non-tidal sea level residuals (values of sea level with the astronomical ocean tide contribution removed), air pressures and along shore winds at Jeddah.

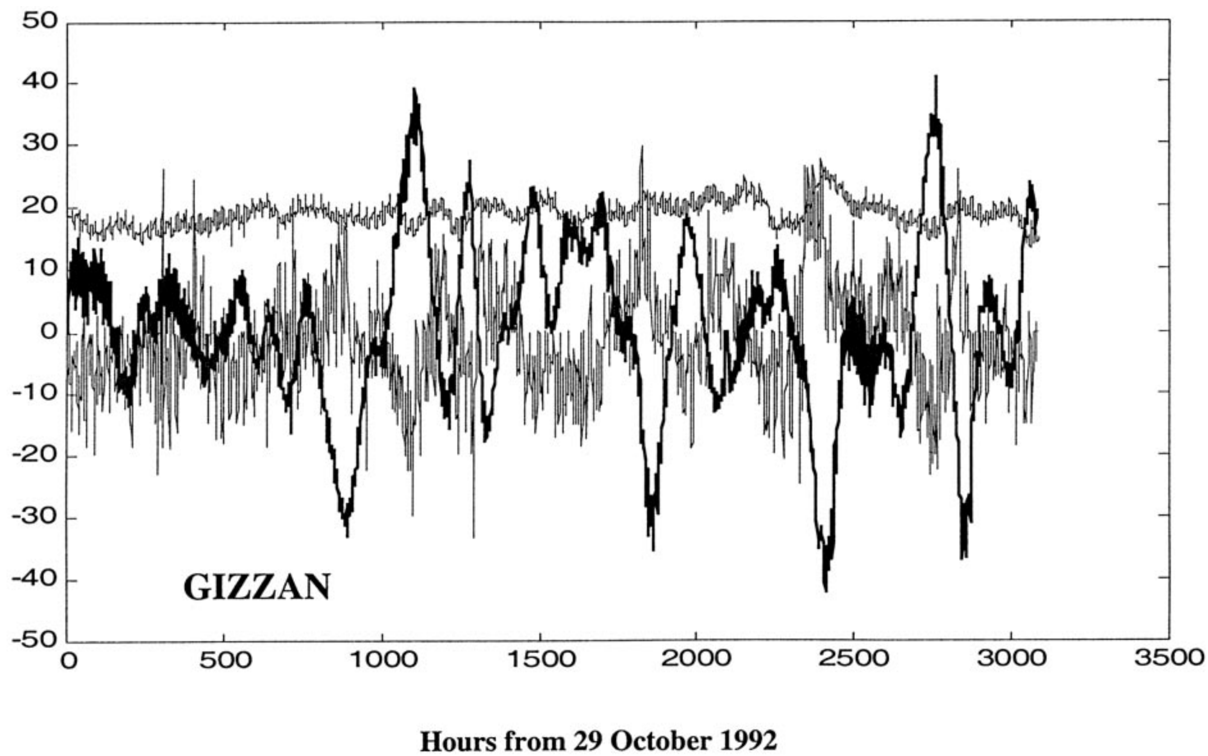

FIG. 3. Relationship between non-tidal sea level residuals (with astronomical tides removed), air pressures and along shore winds at Gizzan, over 130 days.

Seasonal Sea Level Changes

Sultan *et al.* (1995b) showed that at Jeddah seasonal sea level changes are related to the along shore wind stress, whereas at Port Sudan the cross shore component is more important. Typically mean sea level varies seasonally between a maximum 10-20 cm above the average in December/January and a depression of 20-30 cm below the average in August/September. Compared with the small tidal variations, seasonal sea level changes in the Red Sea are particularly significant. The links between seasonal sea level variations in the Red Sea and in the adjacent north west Indian Ocean have been clearly shown by Cromwell and Smeed (1998). They found by analysis of Topex/Poseidon altimeter data that sea surface height residuals at locations in the Red Sea, the Strait and Gulf of Aden indicated a dominant annual cycle and a secondary semi-annual cycle at all locations. The amplitude of the annual cycle over a period 1993-1997 was 18 cm in the Red Sea and 13 cm in the Gulf of Aden. An analysis of coherence between altimeter-derived wind stress and sea surface height residuals shows that the annual cycle is probably related to wind forcing. A weaker semi-annual cycle of 4-8 cm is probably related to the cycle of evaporation.

It is generally accepted that changes in global climate will probably include changes in the pattern and intensity of winds and wind forcing on shallow seas. Because the local and regional meteorology are so important in determining sea level around the Red Sea, changes in the meteorological conditions will be more significant here than in many other regions, where tides are dominant. Any changes in extreme meteorological conditions could lead to increased risks of flooding particularly during the severity of the winter north east monsoon. These effects will be in addition to the increased risks of mean sea level rise. Conversely an increase in the severity of the summer south west monsoon winds could lower sea levels in the Red Sea in the summer months. This could lead to increased coral mortality.

Mean Sea Level

Changes of mean sea level over periods of decades or longer are of great importance to coastal development and for the design of coastal defences. For the oceans as a whole, the level has risen by over 100 metres in the ten thousand years since the last glacial maximum, due to the release of the water which was previously frozen in the polar ice caps. The recent rate of rise is now much slower than previously and is generally estimated to be between 10-25 cm per century. However, there are considerable local variations from this global average, due partly to regional changes in ocean circulation and meteorology, but principally to vertical land movements (Neilan *et al.,* 1998). Although there are no long-term records from the Red Sea itself, measurements in Aden began around 1880. Figure 4 shows the annual mean sea level at both Aden and Bombay over a period of more than 100 years. There are some strong similarities, including the increase of around 10 cm in mean sea level in the period 1940-1950. Figure 5 shows the Aden sea levels held by the IAPSO Permanent Service for Mean Sea Level, on a reduced scale. Data collection has been intermittent and a useful analysis is not possible. There is clearly a need for a long-term commitment to collecting mean sea level statistics around the Red Sea. Earlier figures in this paper were based on data from gauges installed along the Red Sea coast of Saudi Arabia installed by MEPA as proposed by UNESCO to address this need. However, there is obviously a requirement to initiate a more intensive regional monitoring activity, which will complement studies of long term trends in global sea levels determined from the world wide set of coastal gauges and from satellite altimetry.

Together, tide gauges, satellite altimeters and the Global Positioning System (GPS) provide a long-term network for sea level observations, free of local crustal movements. Altimetry maps changes in the open ocean sea surface, while gauges provide information at the coast. GPS measurements of land movements may then be removed from the tide gauge records to reveal long-term local trends in "real" sea level, for comparison with the altimetry. The combined system must be stable, permanent, and globally consistent, while useful at a local level. The study of local impacts can only be assessed by local tide gauges and meteorological measurements, and local knowledge of natural habitats, coastal infrastructure and other systems.

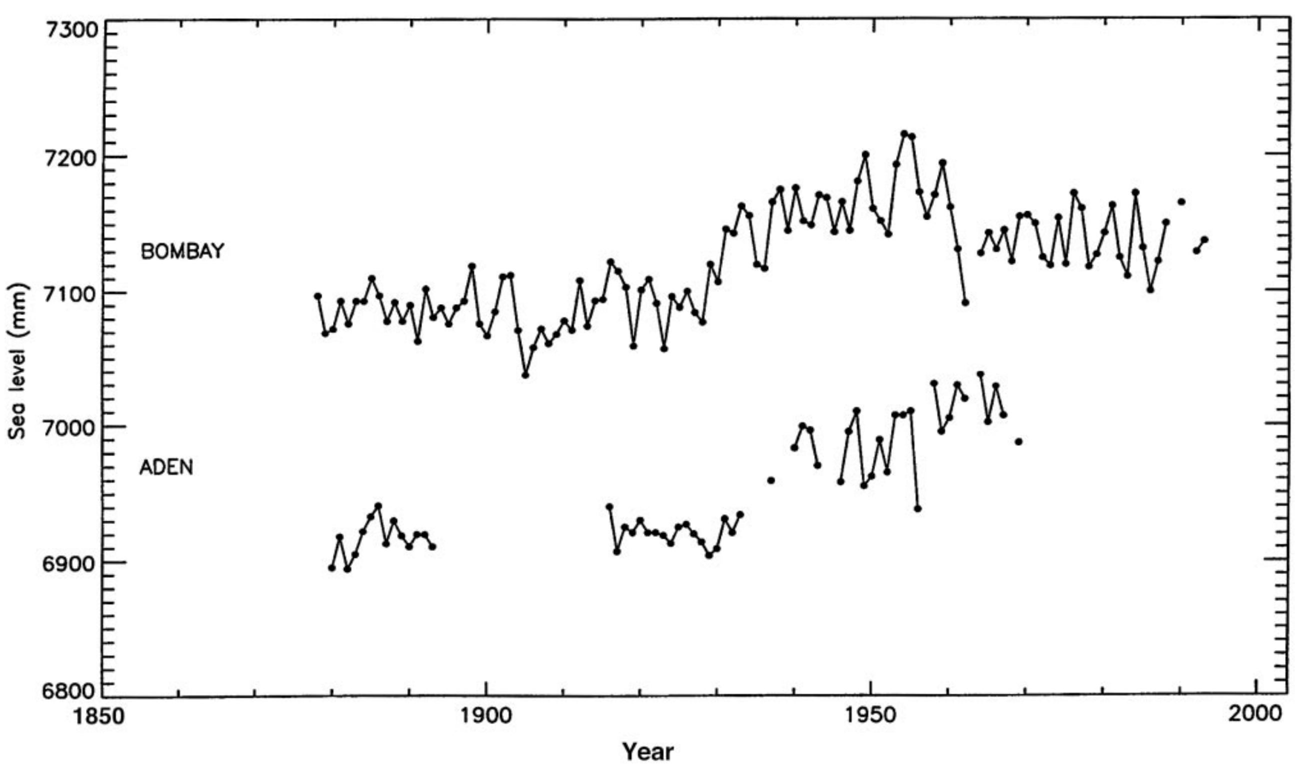

FIG. 4. Annual mean sea level variations at Bombay (1880-present) and Aden, (1880-until the gauge ceased operation).

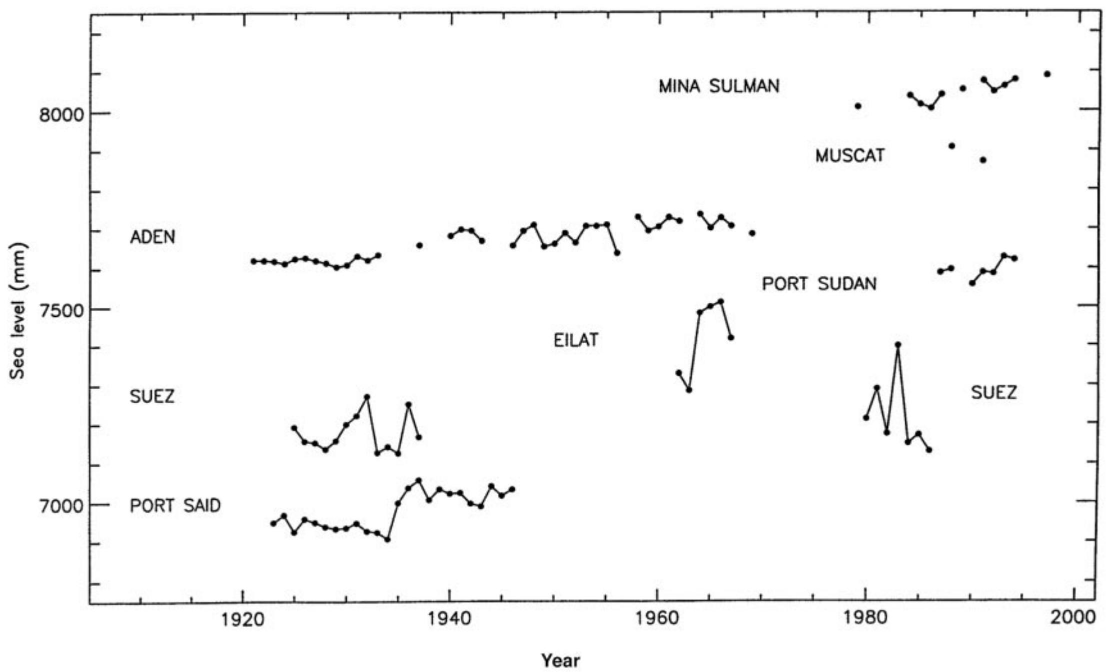

FIG. 5. Available annual mean sea level data held by the Permanent Service for Mean Sea Level. Levels for ports in and near the Red Sea. Note the shortage of high quality long records and the importance of Aden as a strategic reference site.

Adapting to Climate Change

There are several strategies to adapting to climate change. At one extreme, planners may do nothing to prevent the loss of coastal land, corals and amenities. At the other extreme, billions of dollars may be spent to give almost complete protection. Total protection is not possible, as there may always be a small risk of the truly exceptional flood.

When choosing among strategies, planners balance the risks, the value of amenities and the costs of protection. Very approximate global estimates have been published by the Organisation for Economic Co-Operation and Development (OECD) showing that a rather high estimated sea level rise of 1 metre by 2100 would cost $970 billion worldwide, but substantially more than this if coastal resources were either over- or under-protected. Overprotection means too much money is spent on defences; under-protection means that the value of the coastal amenities will be lost. In each local case some kind of cost benefit analysis is necessary.

The cost of defences will include capital for building the protection to reduce risk, payment of interest on the capital, and maintenance. The benefits will include continuing use of amenities and generation of profits, protection of the original value and perhaps reduced compensation payments. In the Red Sea this includes recreational use of coral reefs, and income from tourism. The future values of all of these are very uncertain. This kind of planning is only part of the political and social decision-making process. Only local people can decide what value they place on their assets and amenities. Estimating values is particularly difficult for amenities, which have traditionally been given an economic value in a strict market sense. What value do present generations place on recreational beaches, everglades, mangroves and wetlands? Obviously in countries where these amenities are scarce, the value will be increased. And should we take into account their value for future generations?

The Framework Convention on Climate Change incorporates agreements among governments on the reduction of carbon dioxide emissions. Nevertheless, there will continue to be increases in greenhouse gases for several decades. Whatever action on carbon dioxide is taken, sea levels will probably continue to rise for several hundreds of years before a new equilibrium is reached. Coastal regions need to assess their present risks to flooding, and the vulnerability of their corals. Many countries which have vulnerable, low-lying coastal areas, are now developing local and national monitoring and response programmes, and similar programmes need to be developed in the Red Sea.

Summary

Although sea level changes are natural and inevitable, the difficulties of adapting to these changes will increase. Climate change introduces additional uncertainty and enhanced risks of coral damage and coastal flooding.

All low-lying coastal regions are at risk, but some more than others. Adjustment strategies must depend on the local risks and local evaluation of the impact of flooding. It is impossible to outline a rigorous set of local responses, which should be applied in all cases, even within a limited area like the Red Sea. All coastal communities at risk should continuously measure their sea level changes and periodically assess the risks of flooding and coral damage. In particular, countries are encouraged to make measurements and analyses, which are consistent with and in the context of the Global Ocean Observing System (GOOS). The Global Sea Level Observing System (GLOSS), IOC, and the Global Coral Reef Monitoring Network (GCRMN) have been set up to monitor and help anticipate global change. Governments and local communities can benefit by contributing to GOOS activities and interpreting local changes in a global context.

Finally, we have to recognise the difficulty of maintaining a rational and progressive monitoring and adjustment to changing risks. Serious coral reef damage and coastal flooding are by nature irregular, and so too will be the public and political pressure for remedial actions. Governments world-wide are making strategic responses to the risks of coastal flooding. They are expecting the unexpected and replacing ignorance and uncertainty with scientific risk analysis. Relatively small investment now in monitoring and understanding environmental change will pay dividends in the decades ahead.

Acknowldegements

We acknowledge the meteorological and sea level data provided by the Meteorology and Environmental Protection Administration (MEPA) of Saudi Arabia, for whom one of the authors (D.J. Dixon) was a consultant.

References

Abdelrahman, S.M. (1997) Seasonal fluctuations of mean sea level at Gizan, Red Sea, *Journal of Coastal Research,* **13:** 1166-1172.

Abdelrahman, S.M. (1998) Return values of extremal wind and wave heights in the central zone of the Red Sea, *J. Marine Env. Eng.,* **4:** 201-215.

Cartwright, D.E. (1971) Tides and Waves in the Vicinity of St Helena, *Phil. Trans. R Soc. A,* **270:** 603-649.

Cromwell, D. and **Smeed, D.A.** (1998) Altimetric observations of sea level cycles near the strait of Bab al Mandab, *International Journal of Remote Sensing,* **19**(8): 1561-1578.

Defant, A. (1961) *Physical Oceanography,* Volume 2, Pergamon Press, Oxford, 598 p.

Dullo, W.C. and **Montaggioni, L.** (1998) Modern Red Sea coral reefs: A review of their morphologies and zonation, pp. 583-594, in: *Sedimentation and Tectonics in Rift Basins: Red Sea – Gulf of Aden,* B.H. Purser and D.W.J. Bosence (Ed.), London, Chapman and Hall, 663 p.

Genin, A., Lazar, B. and **Brenner, S.** (1995) Vertical mixing and coral death in the Red Sea following the eruption of Mount Pinatubo, *Nature,* **377:** 507-510.

Harries, D. (1990) Coral bleaching and climate change, *Marine Pollution Bulletin,* **38**(7): 521.

ICRI (International Coral Reef Initiative) (1999) *Renewed Call to Action, The Great Barrier Reef Marine Park Authority,* Townsville, Australia.

Neilan, R.E., Van Scoy, P.A. and **Woodworth, P.L.** (1998) (eds) *Workshop on Methods for Monitoring Sea Level, Proceedings.* California Institute of Technology Jet Propulsion Laboratory Publication 97-17, 202 p.

PERSGA (Protection of Environment of Red Sea and Gulf of Aden) (1998) *A Strategic Action Plan for the Red Sea and Gulf of Aden,* 86 p.

Pugh, D.T. and **Maul, G.** (1999) Coastal Sea Level Prediction for Climate Change. in, *Coastal Ocean Prediction, Coastal and Estuarine Studies,* Chapter 15, **56:** 377-404, American Geophysical Union.

Sheppard, C. and **Dixon, D.J.** (1998) Seas of the Arabian region, in: *The Sea,* Vol. 11, The Global Coastal Ocean: Regional studies and syntheses, A.R. Robinson and K.H. Brink (ed.), pp. 915-931.

Sultan, S.A.R., Ahmad, F. and **Elghribi, N.M.** (1995a) Sea level variability in the central Red Sea, *Oceanologica Acta,* **18**(6): 607-615.

Sultan, S.A.R., Ahmad, F. and **El-Hassan, A.** (1995b) Seasonal variations of sea level in the central part of the Red Sea, *Estuarine, Coastal and Shelf Science,* **40:** 1-8.

Wilkinson, C., Linden, O., Cesar, H., Hodgson, G., Rubens, J. and **Strong, A.E.** (1999) Ecological and socioeconomic impacts of the 1998 coral mortality in the Indian Ocean: An ENSO impact and a warning of future change, *Ambio,* **28**(2): 188-196.

تأثير التغيرات المناخية المحتملة على البيئة البحرية

دافيد بيو ، د. ج. دكسون و ب. ل. وودورث
مركز ساوثهامبتون لعلوم المحيطات و مركز برودمان لعلوم الشواطئ والبحار – بريطانيا

المستخلص. تعتبر الحكومات الآن في مرحلة إعداد التقرير الثالث عن التغيرات المناخية ، والذي نشر في ٢٠٠١م ، ويوجد عدد من التأثيرات الناتجة عن التغيرات المناخية التي تشمل التغير في درجات حرارة المياه ونمط الدوران في البحار والمحيطات . هذا مع أن التغير المباشر يكون في زيادة الاهتمام بمخاطر الفيضانات الساحلية التي تنتج عن ارتفاع درجة الحرارة في المستقبل ، والتي أدت بدورها إلى تكثيف الاهتمام بمخاطر الفيضانات الساحلية التي تنتج عن ارتفاع الحرارة في المستقبل ، والتي أدت بدورها إلى تكثيف الاهتمام من قبل الباحثين وإعداد برامج وتقييم تأثر المناطق بهذه التغيرات . أظهرت قياسات المد والجزر زيادة في منسوب سطح البحر تقدر بحوالي ٢٠سم خلال المائة عام الماضية ، وهناك بعض الاقتراحات تتوقع أن تصل الزيادة إلى ٥٠سم حتى عام ٢١٠٠م ، والتي سوف تؤدي إلى زيادة ملحوظة في مخاطر الفيضانات الساحلية ، كما أن التغيرات في شدة ونمط العواصف الجوية سوف تؤدي إلى فيضانات ذات مخاطر ملموسة .

ويجب على الهيئات المسئولة عن المناطق الساحلية التي تتعرض إلى مخاطر الفيضانات أن تقيم المخاطر الحالية ووضع نظام للتحذير المبكر من المخاطر المستقبلية ، وسوف تقدم هذه المحاضرة بعض الأمثلة للقياسات والدراسات ذات الصلة بالتأثيرات البحرية ، وتناقش أيضًا القياسات الحديثة والاحتمالات المستقبلية في منطقة البحر الأحمر .