

References

BBC News. 2007. Storms lead to major disruption, 21 August 2007. <http://news.bbc.co.uk/1/hi/england/kent/6956195.stm> [Accessed January 2009].

Canterbury City Council. 2008. Report on flooding incident at Whitstable on 21 August 2007, Joint Transportation Board of Canterbury City Council, Item 10, 18 March 2008. [http://www2.canterbury.gov.uk/committee/Data/Joint%20Transportation%20Board/20080318/Agenda/\\$Agenda%20Enclosure%208.doc.pdf](http://www2.canterbury.gov.uk/committee/Data/Joint%20Transportation%20Board/20080318/Agenda/$Agenda%20Enclosure%208.doc.pdf) [Accessed January 2009].

Golding B, Clark P, May B. 2005. The Boscastle Flood: Meteorological analysis of the conditions leading to flooding on 16 August 2004. *Weather* **60**: 230–235.

Kent News. 2007. Whitstable 'no-go' zone as floods hit, 21 August 2007 http://www.kentnews.co.uk/kent-news/Whitstable-_no__go_-zone-as-floods-hit-newsinkent4700.aspx [Accessed February 2009].

Mayes J, Winterton J. 2008. The West Surrey Thunderstorm, 13 August 2006. *Weather* **63**: 50–55.

Sibley AM. 2009. Analysis of the North York Moors storms – 19 June 2005. *Weather* **64**: 39–42.

Correspondence to: Andrew Sibley, Met Office, FitzRoy Road, Exeter, EX1 3PB, UK.

Email: andrew.sibley@metoffice.gov.uk

© Crown Copyright, 2009, published with the permission of the Controller of HMSO and the Queen's Printer for Scotland

DOI: 10.1002/wea.453

A study of sea-level changes in the Kiribati area for the last 16 years

Than Aung, Awnesh Singh and Uma Prasad

University of the South Pacific, Fiji

Introduction

The inhabitants of every Pacific island atoll and island are convinced that the changes they are observing in their islands today are, in many cases, very different from what they observed one or more decades ago. These include extensive coastal erosion, persistent alteration of regional weather patterns and decreased productivity in fisheries and agriculture. Higher sea levels are making some soils too saline for cultivation of crops such as taro, pulaka and yams. Coastal roads, bridges, foreshores and plantations are suffering increased erosion, even on islands that have not experienced inappropriate coastal development. Recent devastating droughts have hit export crops and caused serious water shortages in many Pacific island countries, including the Federated States of Micronesia, Fiji, Marshall Islands, Papua New Guinea, Samoa, Tuvalu, Kiribati and Tonga (Flannery, 2005).

At this point, it is worth referring to the words of the 2006 Australian of the Year. In Chapter 32 – The Last Act of God – of *The Weather Makers*, Prof. Tim Flannery commented that the inhabitants of lands immediately vulnerable to climate change are five atoll countries: Kiribati, Maldives, Marshall Islands, Tokelau and Tuvalu (Flannery, 2005). As a result of the destruction of the world's coral reefs, rising sea levels and the intensifying weather events already in train, it seems inevitable that these nations will be destroyed by climate change during the course of this century.

A brief background history of the study area

Kiribati, officially known as the Republic of Kiribati, is an island nation located in the central tropical Pacific Ocean. It comprises 32 atolls and one island – *Banaba* (Figure 1). The total land area, however, is only approximately 726 km². According to a population estimate in July 2005, it has slightly over 100 000 inhabitants – a population density of 137 people per km². The name Kiribati is pronounced as *kiribas* and is the Kiribati rendering of 'Gilberts' derived from the English name for the main group of islands: the former Gilbert Islands. The island groups include Gilbert Islands, Phoenix Islands and Line Islands (www.wikipedia.org, 2007).

Banaba is an isolated island between Nauru and the Gilbert Islands. It is a raised coral island that was once a rich source of phosphates. The rest of the land in Kiribati consists of sand and reef rock and islets of

atolls or coral islands that rise but a few metres above sea level. In most places it is less than a metre above sea level.

The Australian Project – South Pacific Sea Level and Climate Monitoring Project

In response to concerns raised by the Pacific island countries over the potential impacts of an enhanced greenhouse effect on climate and sea levels in the South Pacific region, the South Pacific Sea Level and Climate Monitoring Project was set up in the early 1990s. It has been fully funded by AusAID for the forum region, which includes Australia, New Zealand, Palau, Nauru, Federated States of Micronesia, Fiji, Marshall Islands, Tuvalu, Kiribati, Vanuatu, Solomon Islands, Papua New Guinea, Samoa, Tonga, Niue and Cook Islands. As part of the project, a SEAFRAME (SEA level Fine Resolution Acoustic

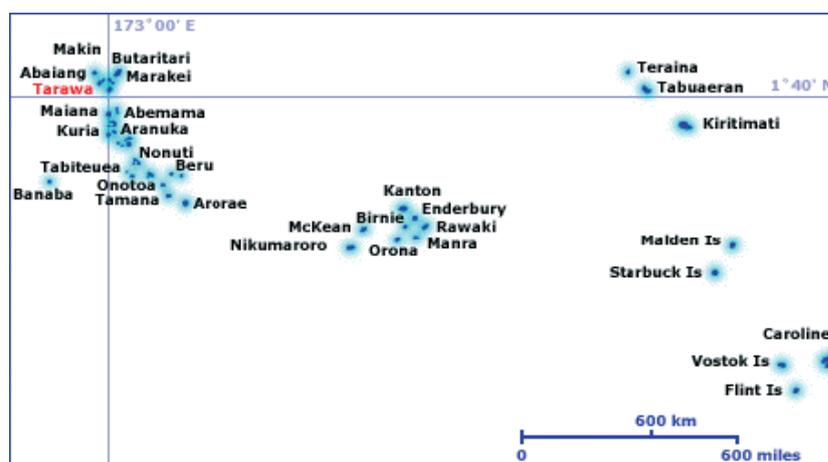


Figure 1. Map of Kiribati. (Source: http://www.spto.org/spto/export/pics/spto/kiribati_map.gif)

Measuring Equipment) gauge was installed in Tarawa, Kiribati, in December 1992. The gauge has been returning high resolution, good scientific quality data, since then.

SEAFRAME gauges not only measure sea level by two independent means, but also a number of ancillary variables, such as air and water temperatures, wind speed, wind direction, wind gust and atmospheric pressure. There is an associated programme of levelling to determine vertical movement of the sea-level sensors due to local land movement. Continuous Global Positioning System (CGPS) measurements are also now being made to determine the vertical movement of the land with respect to the International Terrestrial Frame.

When considering the data length for trend calculations with reasonable certainty, it was appropriate to introduce a term *Node Cycle* – defined as a period of approximately 18.61 Julian years required for the regression of the Moon's nodes to complete a circuit of 360° of longitude. It is accompanied by a corresponding cycle of changing inclination of the Moon's orbit relative to the plane of the Equator, with resulting inequalities in the rise and fall of the tide and speed of the tidal currents (Rockville, 1989).

According to Rockville (1989), the specific 19-year period is adopted as the official time segment over which tide observations are taken and reduced to obtain mean values for tidal datum. It is necessary for standardization because of periodic and apparent secular trends in sea level, that is, a non-periodic tendency of sea level to rise, fall or remain stationary with time. Technically, it is the slope of a least-squares line of regression through a relatively long series of sea-level values. For this reason, the Australian project is set to run in four five-year phases, for a total of 20 years for the whole project. The project is in its final phase now.

Possible impacts of a rise in sea levels

The primary impacts of sea-level rise are generally the inundation of low lands, exacerbation of coastal flooding and erosion, intrusion of salt water into rivers and underground aquifers, changes in sediment deposition patterns and a decrease in the amount of light reaching the sea floor.

Over the past decade, numerous vulnerability assessments have been undertaken in the Pacific island countries. Harvey and Mitchell (2003) indicated that while there has been considerable monitoring of coastal change in the Pacific, the timing, purpose and results of these studies vary considerably. Most are unequivocal in highlighting the extreme physical, social and economic vulnerability of these islands and their people. While erosion is widely cited as an impact of sea-level rise, few studies have provided quantitative assessments of the

magnitude of erosion or the likely mode of physical response of low-lying islands to sea-level rise.

By definition, coastal erosion is the natural process that has been occurring throughout the history of most small islands and causes a long-term loss of land. The more important point is to establish if the erosion is exacerbated by rising sea levels or not. It is to be noted that erosion has increased drastically in many islands as a result of inappropriate human interaction and management. The building of causeways (e.g. to link the islands), the insertion of groins and seawalls, and sand extraction and harbour developments are all activities that have promoted erosion. In Kiribati, for example, there has been extensive monitoring conducted for South Tarawa with a particular focus on the effects that the Nippon Causeway has had on nearby coastal erosion. According to Harvey and Mitchell (2003), much of the coastal change caused by human impact is likely to exceed any impact which could be attributable to natural sea-level change.

Referring to the information from the South Pacific Regional Environmental Program, however, two small uninhabited Kiribati islets – *Tebua Tarawa* and *Abanuea* – disappeared underwater in 1999. *Tebua's* disappearance is a real sign that global warming is making itself felt in the Pacific. While some erosion can be blamed on inappropriate land use practices, the coasts of undeveloped outer islands are also crumbling into the sea. Events like these provide a powerful confirmation that global warming is not just a distant threat but it is underway, with dire implications for the Pacific people (www.wikipedia.org, 2007).

According to McCracken of the US Global Change Research of global warming, a one centimetre rise in sea level can consume one metre or more of beach width towards the sea (Moore, 2002). Kench and Cowell (2002) have provided some very useful information about how low-lying atolls respond to changes in sea level. In particular, they use sediment transport modelling to demonstrate how these coasts are unique in their response to sea-level rise. They show how sediments on low-lying atoll islands could be rolled over towards the lagoon, rather than the general textbook examples of sandy beaches that show a simple readjustment of the beach profile. Sediment transport models were used to provide

estimates of the magnitude of change that would occur under different sea-level-rise scenarios for specific sites, such as South Tarawa in Kiribati. All simulations show that sea-level rise promotes physical changes in shorelines, but the shoreline change does not always result in erosion or net loss of land. This type of information is important for management purposes when examining atoll island vulnerability.

Sea-level trends in the Kiribati region for the last 16 years

Most Pacific islanders are fully aware that the sea level is controlled by many factors; these include the periodic tides, the more occasional violent outcome of cyclones and the prolonged effects of El Niño. All of these changes have a direct effect on their lives. The effects vary widely across the region. Along the Melanesian archipelago, from Manus Island (PNG) to Vanuatu, tides are predominantly diurnal, or once daily, while elsewhere the tides are semidiurnal, that is, each day tends to have two highs and two lows. Tropical cyclones, which are fuelled by heat stored in the upper ocean, tend to occur in the hottest months. They tend not to occur within 5° of the Equator due to the weakness of the *Coriolis* force – a rather subtle effect of the Earth's rotation. Figure 2 depicts the evolution of the short-term sea-level trends recorded at the Tarawa SEAFRAME station from 12 months after its installation.

During this period, four El Niño events took place, including a very severe one during 1997/1998 which generated a significant sea-level drop in the Kiribati region. The usual positive (rising) sea-level trends dropped to negative (falling) values for several months as a result of El Niño. Figures 3(a) and 3(b) show the barometric pressure and sea-level anomalies. It clearly indicates the inverted barometric pressure effect on sea level during the 1997/1998 El Niño.

It should be noted that the early part of the trend line was not stabilized due to the short data length for the statistical analysis calculation. But it shows that the estimates are becoming progressively smaller in magnitude and the lines are becoming smoother and stable. Very high trends in 1995 and low trends in 1996 are too misleading to make any scientific conclusion. The length of the data is approximately a

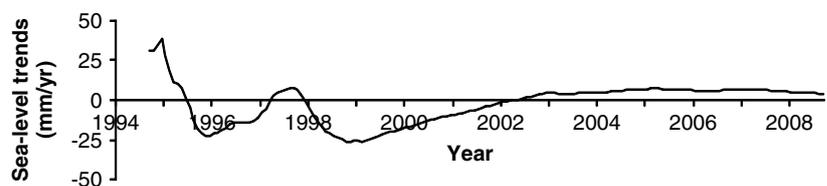


Figure 2. Sea-level trend diagram for Kiribati. (Note: trend values calculation started only after 12 months of data were collected.)

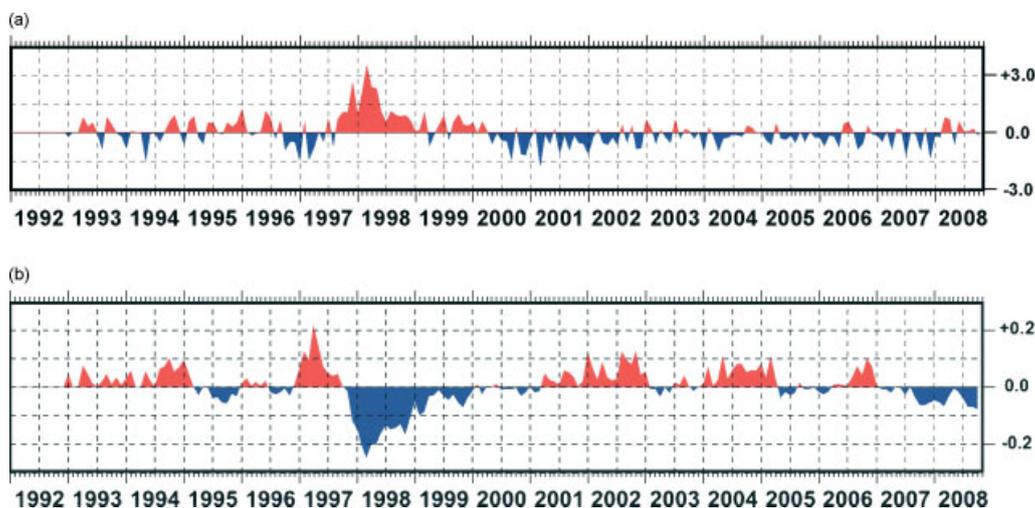


Figure 3. (a) Barometric pressure anomalies to September 2008 (hPa). (b) Sea-level anomalies to September 2008 (m).

period of 16 years, with some significant fluctuations in the trends no longer showing. It must be noted that the gauges located close to the equatorial wave guides, in particular those near to the western boundary of the Pacific, may also undergo substantial fluctuations during the El Niño Southern Oscillation (ENSO) episodes. Analysis of the 16 years of sea-level data by the National Tidal Centre (NTC, 2008) showed that the rate of sea-level rise in the Kiribati region is 3.9mm per year (as at September 2008). The value is very stable; the variations from the previous months are minimal and as small as 0.1–0.2mm per year. The local value is approximately three times larger than the global average of 1–2mm per year. The sea level in Kiribati has risen approximately 6.14cm since December 1992. If this trend continues, land loss will be significant in the next 50 years. The surveying data also shows that for the vertical land movement, the SEAFRAME station area has risen by 2.19mm over the last 11.5 years. Accordingly, the rate of rising land is $\sim +0.2$ mm per year and there is no significant impact on the sea-level-rise trends although it is reducing the rate of sea-level rise slightly. Table 1 summarizes and highlights the critical values of sea-level issues in the Kiribati region.

Sea level has been rising for a long time, long before the global warming issue was introduced. The sea-level-rise issue is not really a new problem in our daily lives. The

real danger may be if the rate of sea-level rise increases with time. The main question is to find if the rate of sea-level rise has accelerated in the recent past. If that is the case, the real danger is getting closer, and Pacific islanders might need to find a new land in which to live out their future.

Looking at the sea-level trends with time shown in Figure 2, it is quite obvious that trends for Kiribati are more or less horizontal since 2001, that is, once the length of data is stabilized for trends calculation and away from the severe effects of the 1998 El-Niño-related sea-level drops. It clearly indicates that the rate of sea-level rise has not been accelerating in the recent past. What must be acknowledged at this stage is that there is no clear evidence of acceleration in sea-level trends over the course of the last century based on the long-term data available elsewhere. More precisely, Mitchell *et al.* (2000) stated that the acceleration assessment from worldwide industrialization over the last two centuries appears to be very slow. The acceleration of the trends identified in their exercise is extremely small, especially when it is taken from just five available long data sets.

Can sea level be predicted accurately?

Before discussion proceeds, it is important to understand what the mean sea level is.

The *mean sea level* is defined as the arithmetic mean of hourly water heights observed over the 18.61-year period. Shorter series are specified in the name as monthly mean sea level and yearly mean sea level (Rockville, 1989). A noteworthy point here is that sea level is the result of the complicated combination of influences such as: (i) daily tides, (ii) meteorological effects (atmospheric pressure and winds, evaporation, precipitation), (iii) thermal effect (volume expansion of water due to global warming, melting land ice), (iv) seismic activity (underwater earthquake, tsunami), (v) oceanographic effects (El Niño, Rossby waves, Kelvin waves, density changes, etc.) and (vi) vertical land movement.

Due to this complex combination of several influences, long-term sea-level trends cannot be predicted accurately at a given location. This has been the main reason for setting up the Australian Project in the Pacific region to monitor the sea level and to calculate accurate sea-level trends. Based on reliable trends, a simple projection for the future may be made for planning and policy-making purposes.

According to Pittock (1999), mean sea level is expected to rise, with some regional variations, by up to ten millimetres per year until well beyond 2100. The preliminary results of Shum *et al.* (2001) indicate that the twentieth-century sea-level rise in the Pacific Ocean was 1.7 ± 0.1 mm per year. This

Table 1

Significant parameters for the sea-level situation in the Kiribati area.

Parameters	Values	Comments
Length of data	16 yrs	Not long enough yet
Sea-level trend	+ 3.9mm/yr	Very small change from the previous months
Sea-level rise	~ 6.14 cm	For the last 16 years
Vertical land movement	$\sim +0.2$ mm/yr	Not significant [slightly reducing sea level]
Number of El Niños	4	Including one that was very severe and prolonged

analysis is based on tide-gauge data with records of 50 years or longer. Using multiple altimeter measurements, it is estimated that the sea-level rise for the Pacific Basin during 1985–1999 was 2.4 ± 1.5 mm per year, which compares well with tide-gauge data analysis during the same time, 2.1 ± 0.3 mm per year.

Hay *et al.* (2003) presented a simple method for computing local projections of mean sea-level rise for the future. To determine the practical implications of the projection of global sea-level rise in particular islands and coastal regions, it is necessary to include both global and local components. They did an estimate for *Kiritimati* – also known as *Christmas Island* – which is part of Kiribati. The island has the greatest land area of any coral atoll in the world with 642 km² and it comprises over 70% of the total land area of Kiribati. For the period between 1990 and 2050, a rise in *Kiritimati* is most likely to be 10 cm, but there is also a 20% chance of it exceeding 18 cm and a 20% chance of it being less than 4 cm.

It is to be noted that the SEAFRAME station is located in Tarawa, and Christmas Island is approximately 3400 km away. It is not realistic to compare the trend values from SEAFRAME stations and make the above prediction.

According to the latest Intergovernmental Panel on Climate Change (IPCC) *Summary for Policymakers* (2007), the following can be noted:

- The estimated rate of sea-level rise based on thermal expansion of water, melting of glaciers and ice caps, Greenland ice sheets and Antarctic ice sheets is 1.1 ± 0.5 mm per year between 1961 and 2003 and 2.8 ± 0.7 mm per year between 1993 and 2003. It indicated that the rate was faster during the last ten years.
- The observed rate of sea-level rise was 1.8 ± 0.5 mm per year between 1961 and 2003 and 3.1 ± 0.7 mm per year between 1993 and 2003.
- Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer term trend is unclear. There is high confidence that the rate of observed sea-level rise increased from the nineteenth to the twentieth century.
- The total twentieth century sea-level rise is estimated to have been 17 ± 5 cm.

This new report suggests that global warming is 'very likely' man-made, this being the most powerful language used by the world's leading scientists. However, these values may change abruptly. For

example, the seismic jolt that unleashed the deadly Solomon Islands tsunami on 2 April 2007 lifted an entire island – *Ranongga* – three metres out of the sea. This is just a seismic effect alone.

Although the prediction of future sea level is impossible, the main component of sea level, namely daily tides, can be predicted quite accurately. However, the local sea-level trends at any particular island are liable to be quite different from global and regional sea-level trends.

Conclusions

Erosion is not the only issue in the low-lying Pacific islands due to the rising sea. Inundation, both permanent and temporary, will penetrate increasingly further inland. According to Nunn (2001), on those low-lying coasts made entirely from permeable rocks – be they consolidated or unconsolidated, bedrock or sediment – saltwater intrusion into groundwater will become an increasing problem as sea levels rise.

In this paper, nearly 16 years of sea-level data from the Australian Project was analysed and the sea-level trend for Tarawa was a rise of 3.9 mm per year (up to September 2008), a total 6.1 cm sea-level rise for the area. If this rate continues, loss of land will be significant in the next 50 years.

While there is always likely to be debate over the scientific accuracy of sea-level trends and the length of data used, Pacific islanders cannot wait indefinitely to see more accurate sea-level-rise results. It is still possible to address some of the uncertainties related to sea-level monitoring; a better understanding of island change is needed to make a better plan and policy for the individual needs of each island. According to Lefale of the New Zealand Met Service, while travelling around the Pacific he found that people were not pessimistic. They are resilient and prepared to adapt to changes. They have been doing it for generations and they will continue to do so (Lefale, 2007).

References

- Flannery T.** 2005. *The weather makers: The history and future impact of climate change*. The Text Publishing Company: Melbourne.
- Harvey N, Mitchell W.** 2003. Monitoring sea-level change in Oceania. *Tiempo: Global Warming and the Third World* **50**: 1–6.
- Hay JE, Mimura N, Campbell J, Fifita S, Koshy K, McLean RF, Nakalevu T, Nunn P, de Wet N.** 2003. *Climate variability and change and sea level rise in the Pacific Islands region: a resource book for policy and decision makers, educators and other stakeholders*. South Pacific Regional

Environment Programme, Ministry of Environment and Apia: Japan.

IPCC. 2007. *Climate Change 2007: The physical science basis. Summary for policymakers*. Cambridge University Press: Cambridge.

Kench P, Cowell P. 2002. Erosion of low-lying reef islands. *Tiempo: Global Warming and the Third World* **46**: 6–12.

Lefale P. 2007. Islanders are resilient: Expert. *The Fiji Times*, Suva, Fiji, 14 April 2007.

Mitchell W, Chittleborough J, Ronai B, Lennon GW. 2000. Sea level rise in Australia and the Pacific, in *Proceedings of the Science Component: Pacific Islands Conference on Climate Change, Climate Variability and Sea Level Rise [Linking Science and Policy]*. Grezchnik M, Chittleborough J (eds). National Tidal Facility: Adelaide. pp 47–57.

Moore CA. 2002. Awash in a rising sea. *International Wildlife* **32**(1). Available online: www.nwf.org/internationalwildlife/article.cfm?articleid=15&issueID=3

NTC (National Tidal Centre). 2008. *Monthly Data Report: September 2008*. South Pacific Sea Level and Climate Monitoring Project: Adelaide.

Nunn PD. 2001. Sea-level changes and their effects on tropical Pacific Island environments: the next hundred years. in *Proceedings of the Science Component: Pacific Islands Conference on Climate Change, Climate Variability and Sea Level Rise [Linking Science and Policy]*. Grezchnik M, Chittleborough J (eds). National Tidal Facility: Adelaide. pp 59–62.

Pittock AB. 1999. Assessing risk to the Pacific Island states from climate change and sea level rise, in *Proceedings of the Third SPREP Meeting on Climate Change and Sea Level Rise in the South Pacific Region*. Kaluwin C, Hay JE (eds). South Pacific Regional Environment Programme: Apia. pp 167–187.

Rockville MD. 1989. *Tide and Current Glossary*. NOAA (National Oceanic and Atmospheric Administration), US Department of Commerce: Washington DC.

Shum CK, Zhou CY, Tseng HZ, Woodworth P. 2001. 20th century sea level change in the Pacific Basin, in *Proceedings of the Science Component: Pacific Islands Conference on Climate Change, Climate Variability and Sea Level Rise [Linking Science and Policy]*. Grezchnik M, Chittleborough J (eds). National Tidal Facility: Adelaide. pp 83–88.

Wikipedia. 2007. *List of places on land with elevations below sea level*. Wikipedia Foundation Inc., available online www.wikipedia.org

Correspondence to: Awnesh Singh, Physics Division, University of the South Pacific, Laucala Campus, Private Bag, Suva, Fiji.

Email: awneshsingh@gmail.com

© Royal Meteorological Society, 2009

DOI: 10.1002/wea.396