

# Sea-level rise at tropical Pacific and Indian Ocean islands

John A. Church<sup>a,b,\*</sup>, Neil J. White<sup>a,b</sup>, John R. Hunter<sup>b</sup>

<sup>a</sup> CSIRO Marine and Atmospheric Research, GPO Box 1538, Hobart, Tasmania, 7001, Australia

<sup>b</sup> Antarctic Climate and Ecosystems Cooperative Research Centre, PB80, Hobart, Tasmania, 7001, Australia

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## Abstract

Historical and projected sea-levels for islands in the tropical Pacific and Indian oceans are a subject of considerable interest and some controversy. The large variability (e.g. El Niño) signals and the shortness of many of the individual tide-gauge records contribute to uncertainty of historical rates of sea-level rise. Here, we determine rates of sea-level rise from tide gauges in the region. We also examine sea-level data from the TOPEX/Poseidon satellite altimeter and from a reconstruction of sea level in order to put the sparse (in space and time) tide-gauge data into context. For 1993 to 2001, all the data show large rates of sea-level rise over the western Pacific and eastern Indian Ocean (approaching 30 mm yr<sup>-1</sup>) and sea-level falls in the eastern Pacific and western Indian Ocean (approaching -10 mm yr<sup>-1</sup>). Over the region 40°S to 40°N, 30°E to 120°W, the average rise is about 4 mm yr<sup>-1</sup>. For 1950 to 2001, the average sea-level rise (relative to land) from the six longest tide-gauge records is 1.4 mm yr<sup>-1</sup>. After correcting for glacial isostatic adjustment and atmospheric pressure effects, this rate is 2.0 mm yr<sup>-1</sup>, close to estimates of the global average and regional average rate of rise. The long tide-gauge records in the equatorial Pacific indicate that the variance of monthly averaged sea-level after 1970 is about twice that before 1970. We find no evidence for the fall in sea level at the Maldives as postulated by Mörner et al. (2004). Our best estimate of relative sea-level rise at Funafuti, Tuvalu is 2 ± 1 mm yr<sup>-1</sup> over the period 1950 to 2001. The analysis clearly indicates that sea-level in this region is rising. We expect that the continued and increasing rate of sea-level rise and any resulting increase in the frequency or intensity of extreme sea-level events will cause serious problems for the inhabitants of some of these islands during the 21st century.

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## 1. Introduction

The islands in the tropical oceans are some of the regions most vulnerable to sea-level rise and the associated impacts of climate change. These impacts include changes in weather patterns (temperature, winds, precipitation etc.), sea-level rise, coastal erosion, changes in the fre-

quency of extreme events including potential increases in the intensity of tropical cyclones/hurricanes, reduced resilience of coastal ecosystems (including bleaching and changed calcification rates of coral reefs) and saltwater intrusion into freshwater resources. Mörner et al. (2004) and Mörner (2004) recently drew attention to the potential vulnerability of the Maldives. However, Mörner et al. (2004) argued that there had been a 30 cm fall in sea-level at the Maldives over the last 50 yrs while Mörner (2004) argued that there had been no global averaged sea-level rise over the decade of the 1990s. Mörner's conclusions

\* Corresponding author. CSIRO Marine and Atmospheric Research, GPO Box 1538, Hobart, Tasmania, 7001, Australia.

E-mail address: [John.Church@csiro.au](mailto:John.Church@csiro.au) (J.A. Church).

concerning a sea-level fall at the Maldives have been firmly rebutted by Woodworth (2005), Woodroffe (2005) and Kench et al. (2005). The impacts of sea-level rise on Tuvalu have also been a subject of considerable controversy (Eschenbach, 2004a,b; Hunter, 2004).

The tropical Pacific and Indian Ocean regions have considerable interannual and decadal sea-level variability associated with the El Niño–Southern Oscillation (ENSO), the Asian–Australian monsoon and phenomena like the North Pacific Decadal Oscillation (Trenberth and Hurrell, 1994; Chambers et al., 2002; Han and Webster, 2002; Church et al., 2004). In short tide-gauge records, this variability may obscure any longer-term sea-level change, or the variability may be misinterpreted as a regional change. For example, annual mean sea-level at some locations can change by as much as 20–30 cm on interannual time scales.

The availability of improved data sets over recent decades should allow more effective separation of the short-term variability from the longer-term sea-level rise. Of particular importance is the high quality data from the TOPEX/Poseidon and Jason-1 satellite altimeter missions (January 1993 to present) that allows the basin-wide scales of sea-level variability to be examined. Also important are the sea-level records from high quality tide gauges at a number of islands in the tropical Pacific Ocean. Many of these were installed in the 1970s or early 1980s to study the evolution of ENSO events and were important elements of the Tropical Ocean Global Atmosphere project (World Climate Research Program, 1985; McPhaden et al., 1998). With an increasing focus on sea-level rise in the late 1980s, the quality of individual gauges, and of the network as a whole, has been improved using modern instrumentation with rigorous datum control (most recently using continuous GPS instruments) and the extension of the network to more locations. For many of these sites, there are now more than 20 yrs of data. However, there are only a few Pacific island records extending over the full 52 yrs examined here.

Modern statistical techniques have also been developed to combine the best attributes of the in situ and satellite data sets; i.e. the longer in situ records and the broad (essentially global ocean) coverage from satellites. These techniques, modeled on approaches used to estimate global surface temperatures over the last century (e.g. Kaplan et al., 1998, 2000; Rayner et al., 2003), use tide-gauge data to estimate the amplitude of empirical orthogonal functions (EOFs) whose spatial structure has been estimated from the satellite altimeter data. Importantly, this technique takes account of the spatial patterns of sea-level variability, rather than regarding variations from the global mean as “noise”. For example, the anti-phase sea-level

movements on either side of the Pacific Ocean are attributed to ENSO, rather than being regarded as unexplained random variations. The technique provides estimates of monthly averaged sea level on a near global (65°S–65°N) 1°×1° ocean grid (essentially the ice free regions; Chambers et al., 2002; Church et al., 2004; Church and White, 2006).

Given the potential vulnerability of the Maldives, Tuvalu and other island states in the Pacific and Indian oceans, we assemble the sea-level data sets described above to provide the best possible estimates of sea-level rise for the latter half of the 20th century for these islands. We also test the veracity of assertions (Mörner, 2004; Mörner et al., 2004) that no significant sea-level rise is occurring. The data sets and techniques used are described briefly in Section 2. The results (Section 3) indicate large interannual variability of the tropical Pacific and Indian ocean region and clear evidence that global average sea level has been rising both over the last decade and the last half of the 20th century. We find no evidence for the 30 cm fall in sea level “in the 1970s to early 1980s” for the Maldives as postulated by Mörner et al. (2004).

## 2. The data sets and methods

### 2.1. Preliminaries

For many studies, tide-gauge and satellite altimeter data are corrected for the “inverse barometer” (IB) response of the ocean to variations in atmospheric pressure as this gives the most useful product for many oceanographic studies. However, most of the data presented here do not include this correction as we are interested in observed or relative sea level — that is, sea level relative to the land at any given site. When we do make the IB correction (Church et al., 2004; Ponte, 2006), we use the atmospheric pressure data from the NCEP–NCAR 50 year reanalysis (Kistler et al., 2001) and assume that sea level responds isostatically to local changes in atmospheric pressure relative to the global over-ocean mean.

Glacial Isostatic Adjustment (GIA, also known as post-glacial rebound (PGR), Mitrovica et al., 2001) compensates tide-gauge or satellite altimeter data for the changes of ocean basin shape and gravity caused by changes in surface loading with the melting of large ice sheets from the most recent glaciations. Most of the data presented here do not include this correction as we are most interested in relative sea level. We have performed the reconstruction with the GIA included to get the best estimate of the global fields, then removed this correction to give the best data set for comparisons with tide-gauge data and to focus on relative sea-level change.

Some tide-gauges records are contaminated by vertical land movement due to processes at a range of spatial scales, from large-scale geological processes (in addition to GIA) to local harbour effects as a result of, for example, land reclamation and groundwater pumping. No correction for these effects is possible in general.

All data presented here have had a seasonal (annual plus semi-annual) signal removed. Tide-gauge data have also been smoothed over  $\pm 2$  months. As we are only interested in changes in sea-level at each location, we have matched the means of the data sets over their common periods for display purposes.

### 2.2. The tide-gauge data set

Most of the tide-gauge data used here (apart from the data for Funafuti, Section 3.3) are monthly mean sea-levels from the data archive of the Permanent Service for Mean Sea-Level (PSMSL; Woodworth and Player, 2003) for January 1950 through December 2001, a one year extension of the data set used by Church et al. (2004). We do not consider tide-gauge data after 2001 because of delays in submission of data sets to the PSMSL. We use primarily RLR (Revised Local Reference) data, but also some Metric data, downloaded from the PSMSL WWW site (<http://www.pol.ac.uk/psmsl/>) in February 2003. The RLR data files are supported by documentation relating measured sea level at each site to a constant local datum over the complete record. The Metric records can have substantial and unknown datum shifts and their use in time series

analysis is generally not recommended. Where such datum shifts have occurred, we have treated the sections before and after the shift separately, as in Church et al. (2004). All records are carefully screened for datum shifts (both jumps and gradual changes). Differences between reconstructed trends (on the  $1^\circ \times 1^\circ$  grid) produced with and without the Metric data are less than  $0.1 \text{ mm yr}^{-1}$  for both the area-weighted mean and standard deviation. Fig. 1 shows the locations referred to in this paper, but the sea-level reconstruction uses data from a global set of island and coastal tide gauges as in Church et al. (2004).

### 2.3. The TOPEX/Poseidon satellite altimeter data set

To estimate global sea-level rise from 1993 to 2001 and to estimate the global covariance structure of sea-level variability, we use the TOPEX/Poseidon along-track data from the Merged Geophysical Data (MGDR-B) records for January 1993 through December 2001 (cycles 11 to 342, 108 months). All standard corrections recommended by Benada (1997), except the inverse barometer correction, were applied. In addition, we applied a correction for a long-term, spatially uniform drift ( $\sim 5 \text{ mm}$  over the first 5 yrs of the mission, then fixed at  $5 \text{ mm}$ ) in the TOPEX/Poseidon TMR (radiometer)-based water vapour path delay correction (Keihm et al., 2000) and the estimated altimeter drift (by comparison of the altimeter surface heights with tide-gauge data; Mitchum, 1998, 2000). The main consequence of the latter correction is that it compensates for the  $\sim 10 \text{ mm}$  jump in measured sea-level when the TOPEX

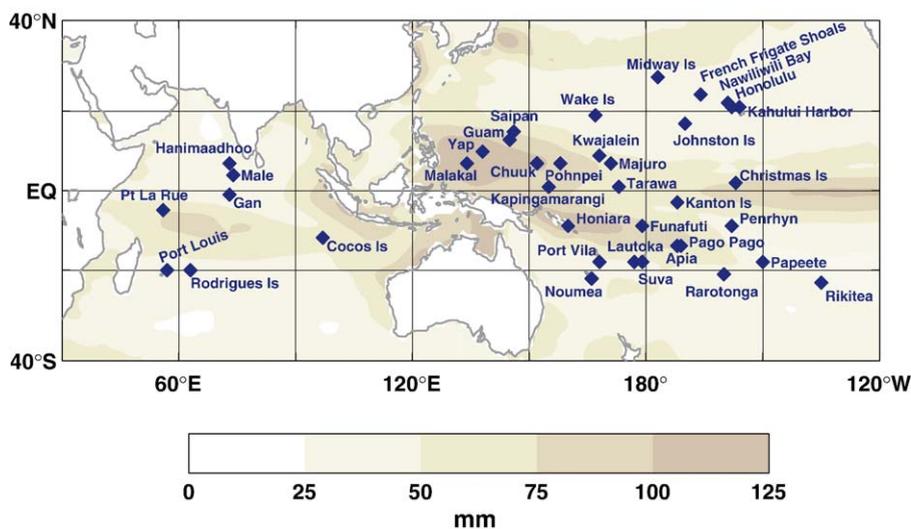


Fig. 1. Location map. A number of sites (Saipan, Kapingamarangi, Port Vila, Lautoka, Apia, Rarotonga and Penrhyn) are not mentioned in the text, but are shown here as data from their short records are shown on Fig. 2a and b. The RMS variability from smoothed, monthly TOPEX/Poseidon data from January 1993 to December 2001 is indicated by the shading.

“side B” altimeter replaced the “side A” altimeter because of age-related problems. The GMSL trend (1993–2001) is  $2.7 \text{ mm yr}^{-1}$  (with no IB or GIA included in this figure).

As we are interested in large space- and time-scale phenomena, monthly estimates of sea-level on a  $1^\circ \times 1^\circ$  grid were obtained by applying a Gaussian filter, with an e-folding scale of 300 km applied over a square with sides of 800 km, to the along-track data. Satellite altimeters measure sea-level relative to the centre of the Earth, and should also be corrected for GIA (Tamisiea et al., personal communication), but as our TOPEX/Poseidon data set has been calibrated against tide gauges (see above), this effect has essentially been addressed to within an error of about  $0.1 \text{ mm yr}^{-1}$ , which is negligible for our purposes.

#### 2.4. The reconstructed global sea-level fields

We use monthly sea-level values from a global reconstruction as described in Church et al. (2004), extended by 1 yr to December 2001. Briefly, this sea-level reconstruction (from January 1950 to December 2001 and on the same  $1^\circ \times 1^\circ$  grid as the TOPEX/Poseidon data) was generated using tide-gauge data (Woodworth and Player, 2003) to estimate the amplitudes of empirical orthogonal functions (EOFs) determined from the 9 year TOPEX/Poseidon data set (Chambers et al., 2002; Church et al., 2004). The first 20 EOFs are used in addition to a spatially constant field (dependent on time but independent of location) which represents the global mean sea-level. This latter field (referred to as “mode 0” in Church et al., 2004) is needed as the EOFs reflect the temporal/spatial variability of sea-level but cannot adequately represent significant changes in global mean sea level. Using EOFs from a restricted period to estimate sea level over a longer period assumes that the large-scale variability can be estimated adequately using these EOFs. This is discussed in Church et al. (2004), Church and White (2006) and Chambers et al. (2002).

The trend in global-mean sea level estimated from this reconstruction is consistent with estimates from tide-gauge data (Douglas, 1991, 1997; Holgate and Woodworth, 2004). Reconstructed sea-level time series at tide-gauge sites also agree well with the original tide-gauge data, even when the tide-gauge data at a location are withheld from the reconstruction (Church et al., 2004). The main advantage of this data set is that it provides estimates of the regional and global variations of sea-level and time series of estimated sea-level at individual locations over a longer period than is often available from individual tide-gauge records alone.

#### 2.5. Uncertainties

The true uncertainty of sea-level trends will be underestimated if the serial correlation of the time series is ignored. In the Indo-Pacific region, the problem is often compounded by substantial interannual excursions in sea level related to ENSO events. We have derived uncertainty estimates in two ways, both techniques yielding similar results. In the first method, the trend was calculated using all the data points in a time series and the resultant uncertainty estimated assuming that the appropriate number of degrees of freedom was given by the record length divided by the integral time scale (Emery and Thompson, 1998, p. 261). The integral time scale was found to be about 3 months. In the second method, the time series was initially averaged into adjacent temporal bins that were sufficiently large for the residual (after trend removal) to be statistically uncorrelated. The uncertainty was then calculated by basing the number of degrees of freedom on the number of bins. The test for correlation was based on the Durbin–Watson statistic (Von Storch and Zwiers, 1999, p. 157) or simply on an upper bound (in our case, 0.2) for the value of the lag-1 correlation (Ostrom, 1990, p. 29). Both tests yielded similar results. All uncertainty estimates are expressed as  $\pm 1$  standard deviation.

All area-averaged trends are either for the whole region covered by the TOPEX/Poseidon data ( $65^\circ\text{S}$ – $65^\circ\text{N}$ , all longitudes) or for the region  $40^\circ\text{S}$ – $40^\circ\text{N}$ ,  $30^\circ\text{E}$ – $120^\circ\text{W}$  (Fig. 1). All such averages are area-weighted means.

### 3. Results

The root-mean-square (rms) variability in sea level for the 9 yrs of satellite data (January 2003 to December 2001, Fig. 1) reaches a maximum of around 100 mm along the equator in the eastern Pacific Ocean (the region of the equatorial cold tongue) and at low latitudes north and south of the equator in the western Pacific. In the Indian Ocean, the variability is a maximum along a band centred at about  $10^\circ\text{S}$  (maximum of about 80 mm) and along the eastern Indian Ocean boundary. This variability (see Church et al., 2004) reflects that the Pacific Ocean region is the centre of the strongest interannual variability of the climate system, the coupled atmosphere-ocean ENSO phenomenon, and the largest sea-level variations in the world on time scales of months to years and space scales of several hundred kilometers and longer. During El Niños, sea level is anomalously high (by tens of centimeters) in the eastern tropical Pacific and low in

the western tropical Pacific. This large interannual variability highlights the difficulty in accurately determining long-term sea-level trends and the need for long, high-quality records, a point that will be evident when we examine the individual tide-gauge records.

The sea-level trends in the Pacific and Indian Ocean over the first 9 yrs of the TOPEX/Poseidon mission (Fig. 2a) demonstrate the impact of this interannual variability. The large rates of sea-level rise over the western Pacific and eastern Indian Ocean (approaching  $30 \text{ mm yr}^{-1}$ ) and sea-level falls in the eastern Pacific and western Indian Ocean (rates approaching  $-10 \text{ mm yr}^{-1}$ )

reflect the (weak) El Niño like conditions in the early years of the TOPEX/Poseidon mission and the more La Niña like conditions in 2001. The trends over the same period from the reconstruction (Fig. 2b) are similar to those from TOPEX/Poseidon (correlation of 0.87), demonstrating the ability of the reconstruction technique to reproduce the large-scale interannual variability, particularly in the tropical Pacific and Indian Oceans. While there is large-scale spatial structure in the pattern of sea-level rise over the TOPEX/Poseidon period (1993 to 2001), a series of studies (see, for example, Leuliette et al., 2004; Church et al., 2004) have clearly demonstrated a global average sea-level rise over this period of about

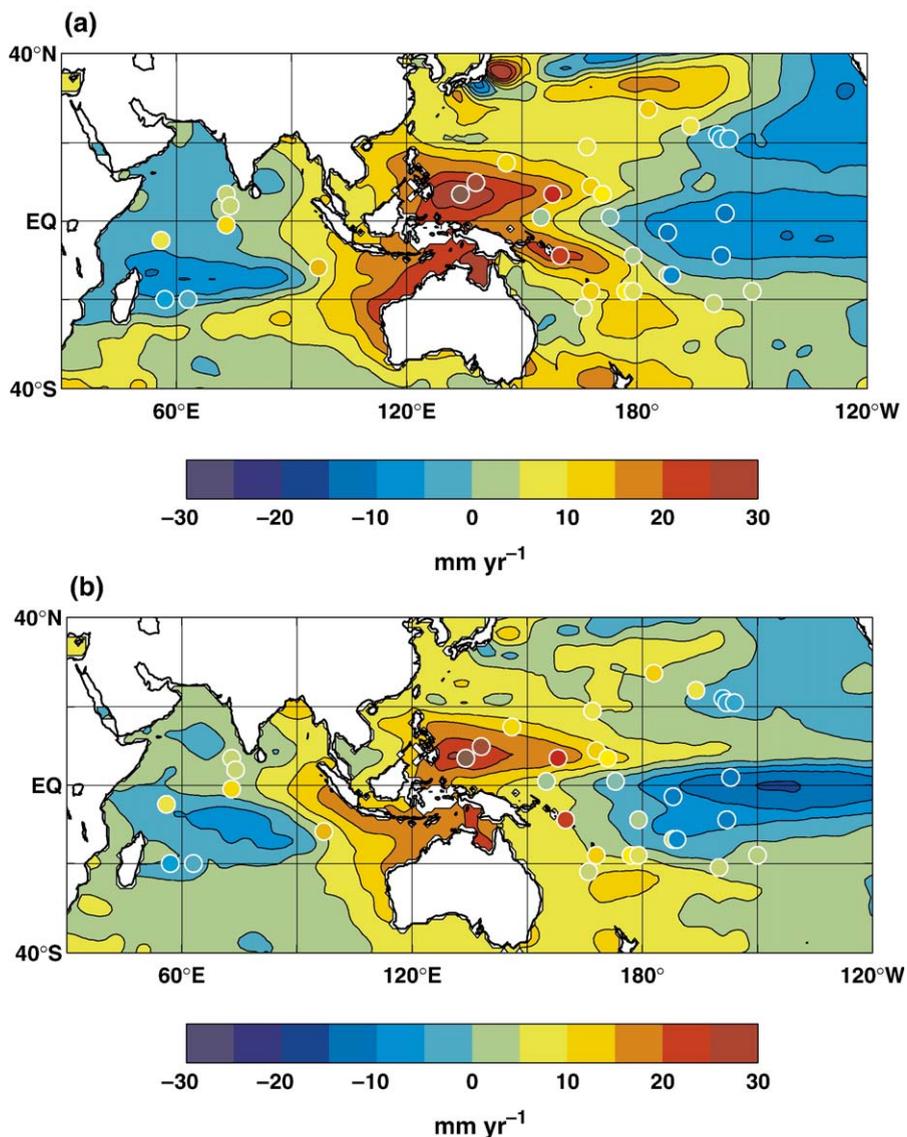


Fig. 2. Map of sea-level trends for (a) TOPEX/Poseidon data and (b) the reconstruction for 1993 to 2001. Tide-gauge trends for the same period are shown where available by the coloured dots.

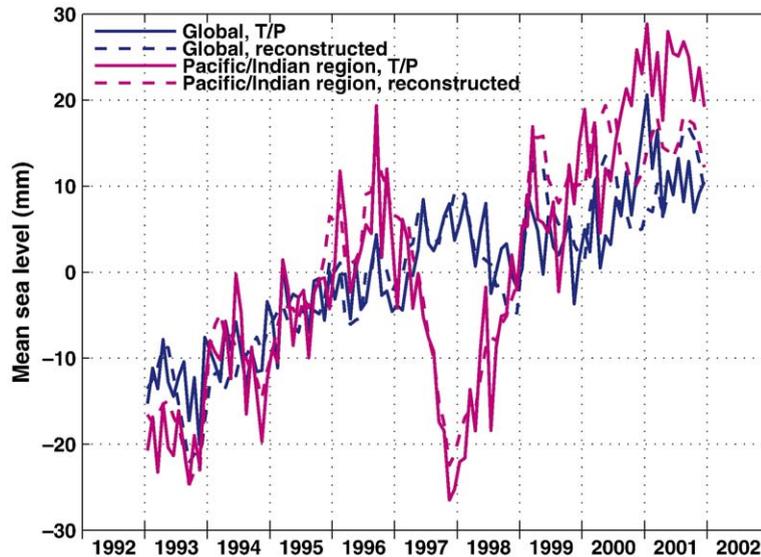


Fig. 3. Global averaged and Pacific/Indian Ocean averaged sea levels over the period 1993 to 2001. The Pacific/Indian Ocean average is for the region shown in Figs. 1, 2 and 6.

$3 \text{ mm yr}^{-1}$  (Fig. 3). For the region shown in Fig. 1 the trends from both the TOPEX/Poseidon data and from the reconstruction are larger (Fig. 3), about  $4 \text{ mm yr}^{-1}$  ( $4.3 \text{ mm yr}^{-1}$  for TOPEX/Poseidon and  $3.6 \text{ mm yr}^{-1}$  for the reconstruction).

Tide-gauge trends give the same overall pattern of sea-level change as the TOPEX/Poseidon and reconstructed sea-levels, but it is clear that the small number of tide-gauge records alone can not give a clear impression of the overall pattern, and the mean trend over the tide gauges would not necessarily give an accurate representation of the trend over the whole region. For example, for the South Pacific Sea Level and Climate Monitoring Project, the average for the 11 longest records (averaging just under 11 yrs in 2004) is  $6.0 \text{ mm yr}^{-1}$  (see page 2 of Mitchell, 2004), substantially larger than the global average value of about  $3 \text{ mm yr}^{-1}$  and the regional average of about  $4 \text{ mm yr}^{-1}$  from both the satellite data and the reconstruction.

### 3.1. Pacific Ocean

We now consider the tide-gauge data (for continuous, or near continuous, records longer than 24 yrs) along with the reconstructed sea levels and the corresponding TOPEX/Poseidon data (Fig. 4). For those locations located within about  $15^\circ$  of the equator (Guam, Chuuk, Yap, Pohnpei, Malakal, Kwajalein, Majuro, Funafuti, Honiara, Pago Pago, Kanton Island and Christmas Island), sea level has large interannual variability (peak-to-peak amplitudes as large as 45 cm) associated with ENSO events (Fig. 4, left-hand side). As a result, estimates of

relative sea-level rise (Table 1, column 5) have large uncertainties. Even for the longest records considered here (52 yrs), the uncertainties are  $0.3 \text{ mm yr}^{-1}$  or greater. As the record length gets shorter these uncertainties increase significantly and are several  $\text{mm yr}^{-1}$  for a number of the shorter records (less than 24 yrs, not included in Table 1).

The few tide-gauge records that commence in the 1950s or earlier (Guam, Chuuk, Kwajalein, Kanton Island and Christmas Island) indicate that interannual variability in sea level prior to 1970 is smaller (e.g. less than 50% at Guam, Kanton Island and Pago Pago) than that of the post 1970 data. This difference in variability is similar to that displayed by the SOI index (Torrence and Webster, 1999). For those locations strongly affected by ENSO events, the reconstructions reproduce much of the observed variability. The average correlation between the reconstructed and observed sea levels is 0.88 and the residual variance is 23.4% of the observed variance.

For the higher latitude gauges (Wake Island, Noumea, Suva, Midway Island, Johnston Island, French Frigate Shoals, Nawiliwili Bay, Honolulu, Kahului Harbour, Papeete and Rikitea; Fig. 4, right-hand side), the variability is of reduced amplitude but higher frequency, compared with stations nearer the equator. At least part of this variability is thought to be a result of westward propagating Rossby waves (Fu and Chelton, 2001). Firing et al. (2004) have also discussed the role of large-scale wind variability in forcing sea-level perturbations at Honolulu. These Rossby waves will be largely eliminated from the satellite altimeter data used here by the spatial filtering and will not be well represented in the

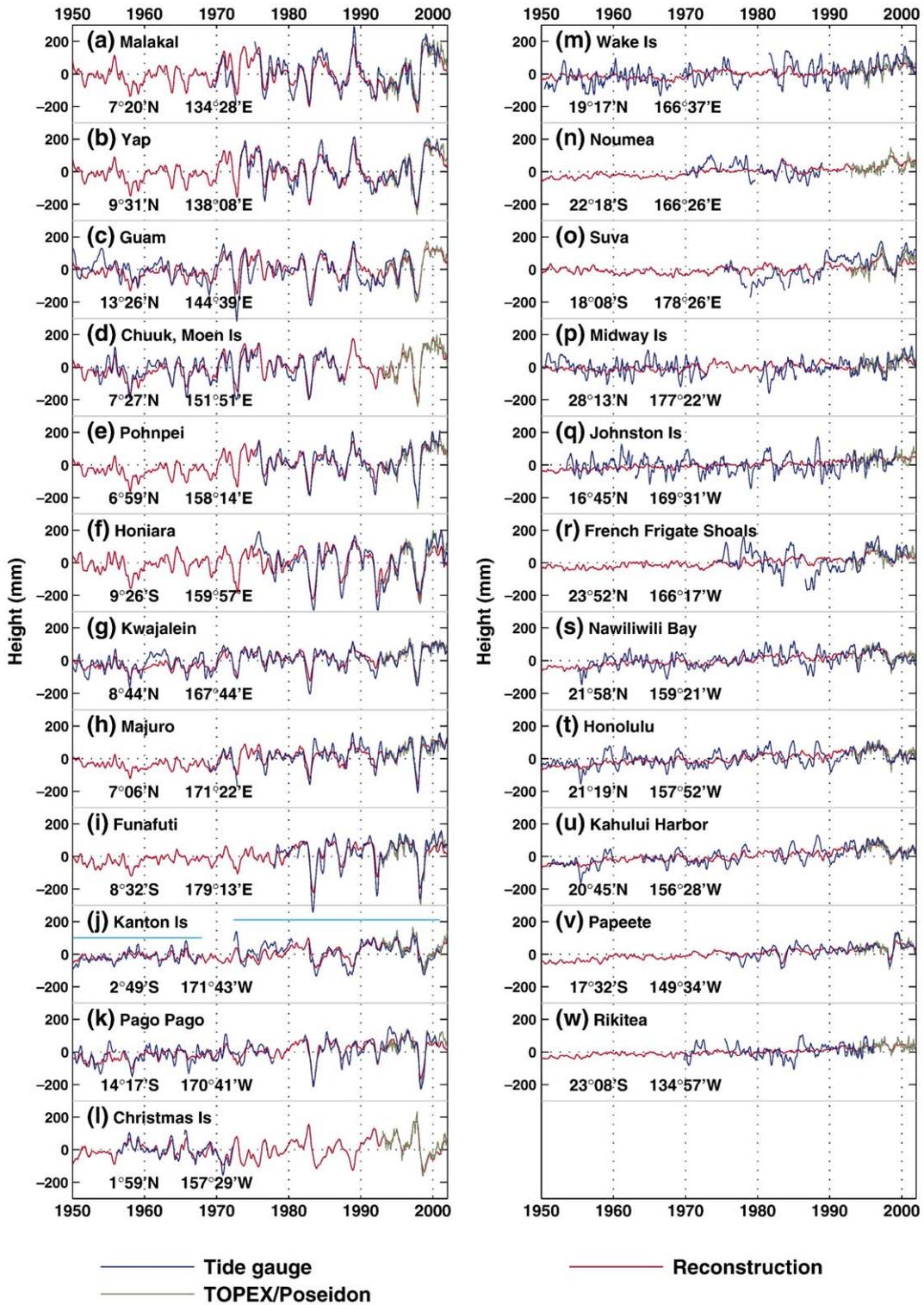


Fig. 4. Time series of tide-gauge (blue), TOPEX/Poseidon (green) and reconstructed sea level (red) for Pacific Ocean sites with more than 24 yrs of tide-gauge data. The light blue lines on panel (j) show the time spans of the two separate records for this site.

Table 1  
Locations, time spans and sea-level trends for Pacific Ocean locations with more than 24 yrs of data

Location	Position	Time span	Years	Tide-gauge trend	Relative recons trend (tide-gauge time span)	Tide-gauge trend with GIA and IB	Relative recons trend (52 yrs)
Malakal	134°28'E 7°20'N	06/1969 – 12/2000	32	1.0±1.2	−0.3	1.5	0.5
Yap	138°08'E 9°31'N	04/1973 – 12/2000	28	−0.4±1.3	−0.8	0.1	0.8
Guam	144°39'E 13°26'N	01/1950 – 11/1997	48	−0.6±0.5	0.5	−0.3	1.1
Chuuk Moen Is	151°51'E 7°27'N	11/1952 – 10/1987	35	0.9±0.7	2.1	1.4	1.7
Pohnpei	158°14'E 6°59'N	04/1975 – 12/2000	26	1.8±1.3	1.2	2.4	1.8
Honiara	159°57'E 9°26'S	12/1974 – 12/2001	27	−0.1±1.6	0.2	0.3	0.6
Kwajalein	167°44'E 8°44'N	01/1950 – 12/2001	52	1.3±0.3	1.9	1.9	1.9
Majuro	171°22'E 7°06'N	10/1968 – 12/2001	33	2.8±0.6	2.3	3.3	2.1
Funafuti	179°13'E 8°32'S	11/1977 – 12/2001	24	2.3±1.5	1.0	2.8	1.6
Kanton Is	171°43'W 2°48'S	01/1950 – 12/1967	18	2.3±0.8	0.7	3.0	1.4
Kanton Is	171°43'W 2°49'S	05/1972 – 12/2000	29	−0.4±0.8	2.0	0.1	1.4
Pago Pago	170°41'W 14°17'S	01/1950 – 08/2000	51	1.6±0.3	1.8	2.1	1.8
Christmas Is	157°29'W 1°59'N	02/1974 – 12/2000	27	−0.1±1.3	1.5	0.6	0.9
Wake Is	166°37'E 19°17'N	06/1950 – 12/2001	52	2.0±0.3	1.2	2.5	1.2
Noumea	166°26'E 22°18'S	03/1967 – 12/2000	34	0.2±0.4	1.8	0.9	1.7
Suva	178°26'E 18°08'S	05/1975 – 12/2001	27	6.7±0.8	1.4	7.3	0.8
Midway Is	177°22'W 28°13'N	01/1950 – 12/2001	52	0.3±0.3	0.8	0.9	0.7
Johnston Is	169°31'W 16°45'N	06/1953 – 04/1999	46	0.4±0.3	1.3	0.9	1.4
French Frigate Shoals	166°17'W 23°52'N	07/1974 – 12/2000	27	1.0±1.0	1.9	1.5	1.5
Nawiliwili Bay	159°21'W 21°58'N	01/1955 – 12/2001	47	1.3±0.3	1.7	1.8	1.7
Honolulu	157°52'W 21°19'N	01/1950 – 12/2001	52	1.3±0.2	1.9	1.8	1.9
Kahului Harbor	156°28'W 20°45'N	01/1951 – 12/2001	51	2.1±0.2	2.0	2.5	1.9
Papeete	149°34'W 17°32'S	07/1975 – 12/2001	27	2.9±0.5	2.2	3.4	1.8
Rikitea	134°57'W 23°08'S	10/1969 – 02/1996	26	1.0±0.6	1.6	1.3	1.3

EOFs used in the reconstruction. As a result, the reconstructed sea-levels do not reproduce much of this high frequency variability but they do reproduce some of the major features and the long-term trends. The records for Suva and French Frigate Shoals have gaps in the sea-level data and the character of the record is somewhat different from nearby locations, calling into question the datum stability of these two gauges.

The significant interannual variability indicates the need for long records to reliably estimate the rate of sea-level rise from individual sites. For example, even for the 52 year long record from Kwajalein, the uncertainty in the relative sea-level trend is as large as  $\pm 0.3 \text{ mm yr}^{-1}$ . The stated uncertainties (Table 1) are from the variability in the sea-level records only.

For the few Pacific Island records greater than 50 years length (6 locations in Table 1), the average rate of relative sea-level rise is  $1.4 \text{ mm yr}^{-1}$ . The corresponding average rate for relative sea-level rise from the reconstructions of  $1.6 \text{ mm yr}^{-1}$  is not significantly different. After GIA and inverse barometer corrections, the mean (absolute) tide-gauge trend is  $2.0 \text{ mm yr}^{-1}$ , consistent with the global average rate of sea-level rise.

For the Pacific Ocean, there are 23 locations with 24 or more years of data (Table 1). Excluding the two locations with apparent problems in the record (French Frigate

Shoals and Suva, both of which have jumps and trends that are anomalous compared with “nearby” locations, see above) and Funafuti (contaminated by vertical land movement, see Section 3.3), and using the longer Kanton Island record, the average rate of relative sea-level rise for the remaining 20 locations is  $1.0 \text{ mm yr}^{-1}$  for the tide-gauge data and  $1.3 \text{ mm yr}^{-1}$  for the reconstructions (for the same period). However, the observations contain a larger range of rates of relative sea-level change, presumably as a result of poorly quantified vertical movements (see Section 3.3 for an example), the large interannual sea-level variability and the fact that the reconstruction does not reproduce some of the smaller-scale variability. After making the GIA and inverse barometer corrections, the corresponding rates of (absolute) sea-level rise are  $1.5 \text{ mm yr}^{-1}$  for the observations and  $1.6 \text{ mm yr}^{-1}$  for the reconstructions, again consistent with global average rates of sea-level rise.

### 3.2. Indian Ocean

There are far fewer island tide gauges in the Indian Ocean than the Pacific Ocean (only seven open-ocean island sites north of  $40^\circ\text{S}$ ; Fig. 5) and the records are much shorter. There is significant interannual variability in sea-level in the southern Indian Ocean (the maximum is at about  $10^\circ$  to  $20^\circ\text{S}$ ) but there is low variability near

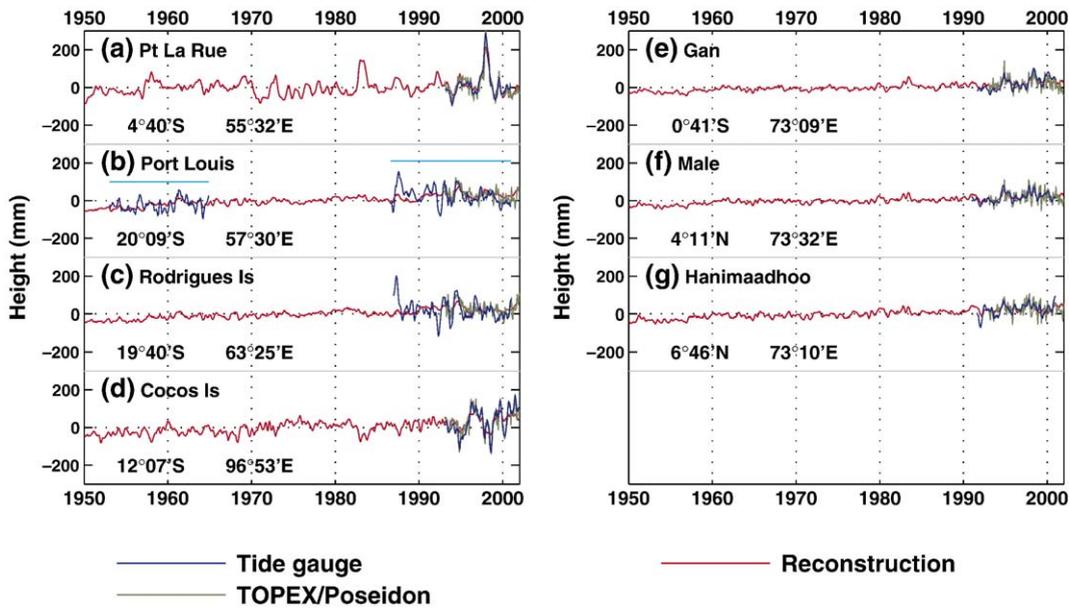


Fig. 5. Time series of tide-gauge (blue), TOPEX/Poseidon (green) and reconstructed sea level (red) for Indian Ocean sites. The light blue lines on panel (b) show the time spans of the two separate records for this site.

the Maldives. The two longest Indian Ocean records (starting in 1986) are from Port Louis (20°9'S, 57°30'E; 1953 to 1964 and a separate record from 1986 to 2000) and 600 km to the east at Rodrigues Island (19°40'S, 63°25'E; 1986 to 2000). The data from the two sites have similar variability (correlation 0.72, significant at the 99% level) with Rodrigues Island leading by 2 months, presumably as a result of westward propagation and/or advection of sea-level anomalies. The observed variability from TOPEX/Poseidon and tide-gauge data for both sites is similar, both having greater variance than the reconstructed sea levels. The greater variability of the tide-gauge records is likely a result of both mesoscale variability and Rossby wave influence and the fact that the reconstruction technique only captures large-scale signals. Despite these differences, the tide-gauge and reconstructed trends have some similarities over the common periods. Both these records show relative sea-level falling at rates of about  $3 \pm 2 \text{ mm yr}^{-1}$  from 1986 to 2000. The satellite altimeter data starting in 1993 also shows sea-level falling in this region. An earlier 12 year record for Port Louis (1953 to 1964) indicates a sea-level rise of about  $2 \text{ mm yr}^{-1}$ , and these results together demonstrate again that short decadal changes may not be representative of long-term trends. Similarly the record from Cocos Island (1993 to 2000) is too short to give a reliable long-term trend. Here the large variability is well reproduced in the reconstruction and the estimated trend from the observations is large at  $12 \pm 5 \text{ mm yr}^{-1}$ . Our

error estimate is likely to be substantially underestimated because the record is so short that it is not possible to reliably estimate an integral time scale. The reconstructed sea levels over the longer 1950 to 2001 period give rates of relative sea-level rise of 1.5, 1.3 and 1.5  $\text{mm yr}^{-1}$  (with error estimates of about  $0.5 \text{ mm yr}^{-1}$ ) at Port Louis, Rodrigues and Cocos Islands respectively.

In the equatorial band, the three locations in the Maldives (Gan, 0°41'S; Male, 4°11'N; Hanimaadhoo, 6°46'N) each have short records, only starting in 1992. The variability of these three records (remembering that all records have had the seasonal signal removed and have then been smoothed) is smaller than at Port Louis and the three records are strongly correlated with each other (correlations of 0.53, 0.73 and 0.67 between the three pairs, all significant at the 99% level) and with the reconstruction (correlations of 0.85, 0.64 and 0.82). As found by Singh et al. (2001), we find that the rates of sea-level rise are large in these very short records ( $8.4 \text{ mm yr}^{-1}$ ,  $3.7 \text{ mm yr}^{-1}$ , and  $4.4 \text{ mm yr}^{-1}$ , respectively). (Note however that this result is in contrast to Mörmner et al. (2004) who state, but do not justify, that the records “reveal a total absence of any secular trend”.) We do not expect the rates from these short records to be representative of longer-term trends. Our error estimates of less than  $2 \text{ mm yr}^{-1}$  (Table 2) are likely to be substantially underestimated because the record is so short that it is not possible to reliably estimate an integral time scale. Also, these gauges may be significantly affected by vertical land motion. The rates over the

Table 2  
Locations, time spans and sea-level trends for Indian Ocean locations

Location	Position	Time span	Years	Tide-gauge trend	Relative recons trend (tide-gauge time span)	Tide-gauge trend with GIA and IB	Relative recons trend (52 yrs)
Pt La Rue	55°32'E 4°40'S	02/1993 – 12/2000	8	5.6±6.6	–1.6	5.2	0.5
Port Louis	57°30'E 20°09'S	01/1953 – 11/1964	12	1.9±1.5	3.7	2.6	1.5
Port Louis	57°30'E 20°09'S	08/1986 – 12/2000	14	–3.7±1.5	1.8	–3.0	1.5
Rodrigues Is	63°25'E 19°40'S	12/1986 – 12/2000	14	–3.6±1.9	0.7	–2.6	1.3
Cocos Is	96°53'E 12°07'S	01/1993 – 12/2001	9	12.1±4.6	5.1	10.7	1.5
Gan	73°09'E 0°41'S	08/1991 – 12/2000	9	8.4±1.7	3.5	7.6	1.0
Male	73°32'E 4°11'N	12/1990 – 12/2000	10	3.7±1.4	2.0	3.1	1.0
Hanimaadhoo	73°10'E 6°46'N	08/1991 – 12/2000	9	4.4±1.9	1.3	3.3	1.2

52 year period from the reconstruction are 1.0, 1.0 and 1.2 mm yr<sup>–1</sup> at the three sites.

Woodroffe (2005) uses geological evidence to infer rates of sea-level rise over recent decades. He gives geological evidence of a net increase of 6 mm or less in sea-level over the 20–30 year period up to 1989 at Veymandoo, Kolamadulu Atoll in the Maldives. This is consistent with our reconstructed time series for the Maldives where our reconstructed time series at Male (our closest site) gives a rate of 0.4 mm yr<sup>–1</sup> over 1960–1989 — consistent with the mean rate of 0.2 to 0.3 mm yr<sup>–1</sup> implied by the (maximum) 6 mm rise over 20–30 yrs from the geological data.

Further west at Port La Rue (4°40'S), the variability is again high in the short (less than 10 yrs) record but the variability is well represented in the reconstruction. The 52 year relative trend at this site is 0.5 mm yr<sup>–1</sup>.

### 3.3. Sea level at Funafuti, Tuvalu

Sea-level change at Funafuti, Tuvalu has been the subject of intense interest as a result of Tuvalu's low-lying nature and reports that flooding is becoming increasingly common. There are two records available at Funafuti: the first record (from a gauge operated by the University of Hawaii Sea Level Centre (UHSLC)) commences in 1977 and the second (from a gauge operated by the Australian National Tidal Centre (NTC)) in 1993. Eschenbach (2004a,b) quotes (but does not substantiate) a “best estimate” of the rate of rise of 0.07 mm yr<sup>–1</sup>, apparently based on an analysis of Mitchell et al. (2001) for the period 1977–1998, with the “likely” (but, again, unsubstantiated) range of –1 to 0.5 mm yr<sup>–1</sup> based on surrounding gauges and an estimate of ocean thermal expansion. Note that the period 1977–1998 ends at the peak of the 1997/98 ENSO event and thus the estimate of 0.07 mm yr<sup>–1</sup> is biased low relative to the long-term trend.

A thorough analysis of survey data at Funafuti (Kilonsky, personal communication) shows that the land

adjacent to the UHSLC gauge is sinking relative to the land adjacent to the NTC tide-gauge benchmark (about 2.5 km away) by 0.6 mm yr<sup>–1</sup>. This tilting may be caused by tectonic movement or (most probably) local subsidence (for example, due to groundwater withdrawal) and demonstrates that even on a single island, the relative sea-level trend may differ by as much as 0.6 mm yr<sup>–1</sup>. In addition, the UHSLC gauge is sinking on its foundations by an additional 0.6 mm yr<sup>–1</sup>, giving a total sinking rate for the UHSLC gauge of 1.2 mm yr<sup>–1</sup>.

Detailed analysis of the Funafuti data from 1978 to 2001 inclusive (Hunter, 2004; the original 2002 report available at <http://staff.acecrc.org.au/~johunter/tuvalu.pdf>) indicates a sea-level rise relative to the NTC tide-gauge benchmark (which is believed to be on stable foundations) of 0.8±1.9 mm yr<sup>–1</sup>. If the data from the UHSLC gauge are used directly with no allowance for the apparent sinking of the tide gauge, the calculated trend is substantially larger. The rate of relative sea-level rise (over the time span of the record) from the reconstructed sea-level at Funafuti is 1.0 mm yr<sup>–1</sup>, in much better agreement with the Hunter estimate and apparently not contaminated by the subsidence of the older tide-gauge. Over 1950 to 2001, the relative rate of sea-level rise at Funafuti estimated from the reconstruction is 1.6±0.5 mm yr<sup>–1</sup>.

A more recent analysis using tide-gauge data from 1978 to 2004 inclusive indicates a sea-level rise of 2.3±1.6 mm yr<sup>–1</sup> relative to the NTC tide-gauge benchmark. This is higher than, but statistically consistent with, the earlier estimate of 0.8±1.9 mm yr<sup>–1</sup>. Taken together, we conclude that a best estimate of the rate of relative sea-level rise at Funafuti is 2±1 mm yr<sup>–1</sup>.

### 3.4. Pattern of sea-level rise for 1950 to 2001

Since the altimeter record is short, we use the reconstructed sea levels to estimate the pattern of relative sea-level rise over the period from January 1950 to December

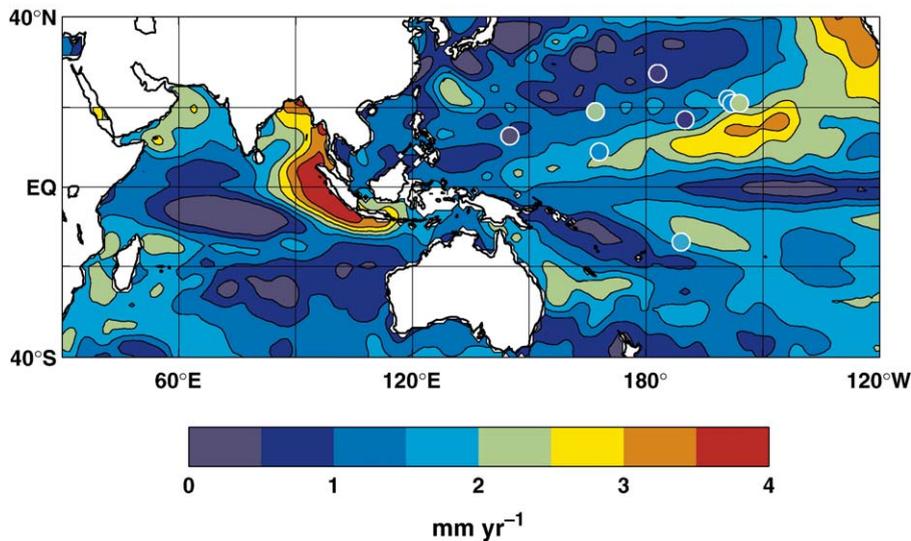


Fig. 6. Map of sea-level trends from the reconstruction over the 52 year period. Trends from the longer tide-gauge records are also shown by the coloured dots.

2001 (Fig. 6). It should be noted that the scale used in Fig. 6 (for the 52-year reconstruction) is about an order of magnitude smaller than the scale used in Fig. 2 and that the rates of sea-level change are more spatially uniform. This smooth pattern is the result of averaging over a number of ENSO events and as a result the rate of change not being overwhelmingly influenced by a single event. The average rate of sea-level rise over this region is  $1.45 \text{ mm yr}^{-1}$ , which, after the subtraction of  $\sim -0.3 \text{ mm yr}^{-1}$  for GIA (giving about  $1.75 \text{ mm yr}^{-1}$ ), is close to the global average rate estimated by Church et al. (2004). The maximum rate is just over  $4 \text{ mm yr}^{-1}$  southwest of Sumatra in the eastern equatorial Indian Ocean and the minimum is close to  $0 \text{ mm yr}^{-1}$  just south of the equator in the central Indian Ocean. In the Pacific, the major large-scale features are a maximum in the rate of sea-level rise in a tongue-like feature in the north-eastern Pacific and a minimum along the Equator and in the western equatorial Pacific Ocean (particularly east of Papua New Guinea). Also shown on Fig. 6 are the trends from the 9 longest island tide-gauge records over the period 1950 to 2001. These gauges are in general agreement with the reconstruction but stronger confirmation of the patterns is not possible with the available in situ data. The gradient in sea-level rise (low in the north-west and high in the south-east) along the Hawaiian island chain ( $21^\circ\text{N}$ ,  $157^\circ\text{W}$ ) is confirmed from the estimates of ocean steric sea-level trends and tide-gauge records corrected for gross vertical motion due to volcanism estimated using GPS data (Caccamise et al., 2005). Lombard et al. (2005) show two estimates of ocean steric height trends. Both of these estimates have a tongue

of high sea-level rise in the north east Pacific, a minimum in rise in the western equatorial Pacific and in a band across the South Indian Ocean, consistent with the reconstructed patterns and the low rates of rise from the geological data (Woodroffe, 2005). However, there are also significant differences between the estimates and in particular the maximum south-west of Sumatra is not as strong in these steric height estimates as in the reconstruction.

#### 4. Conclusions

For 1993 to 2001, the altimeter data and the reconstructed sea levels show the average sea level in the region covered by Fig. 1 rising at about  $4.3 \text{ mm yr}^{-1}$ , similar to but slightly larger than the regional TOPEX/Poseidon trend of about  $3.6 \text{ mm yr}^{-1}$ . A number of recent studies (Leuliette et al., 2004; Church et al., 2004; Holgate and Woodworth, 2004; Cazenave and Nerem, 2004) also confirm the global average sea-level rise from altimeter studies, with estimates varying over a small range depending on the details of the calculation. In direct contrast, Mörner (2004) shows a plot (his Fig. 2) of sea-level variations from October 1992 to April 2000, based on TOPEX/Poseidon data, ostensibly showing that there is no rise in GMSL. This is described as being “raw data”, and appears to be cycle-by-cycle (10 day) averages of global mean sea-level. Unfortunately, there is neither a description of the data that were used to produce this figure, nor a reference to its source. In order to be a meaningful estimate of global mean sea-level, a number of corrections would have been necessary, including wet

tropospheric path delay, dry tropospheric path delay, ionospheric path delay, sea-state bias and tides, but it is unclear which, if any, of these well-known and understood corrections have been applied.

The altimeter data and the reconstructions reveal a large-scale pattern of sea-level change over this period — sea-level falling in the eastern Pacific and the western Indian Ocean and rising in the western Pacific and eastern Indian Ocean. The rates of change are large and are characteristic of interannual climate variability. There is in general a good agreement between the tide-gauge data, the altimeter data and the reconstructions for the period of overlap. In the Indian Ocean, the tide-gauge records at the Maldives indicate large rates of relative sea-level rise in agreement with Singh et al. (2001) and Woodworth (2005), and in disagreement with Mörner et al. (2004).

For the 1950 to 2001 period, there is a good agreement between the observed and the reconstructed sea-level variability in the equatorial region. However, there are only six complete island tide-gauge records, all in the Pacific Ocean. The average trend for these records gives a relative sea-level rise of  $1.4 \text{ mm yr}^{-1}$  ( $1.6 \text{ mm yr}^{-1}$  from the reconstructed sea-level at these locations). Corrected for GIA and changes in atmospheric pressure, the average tide-gauge trend is  $2.0 \text{ mm yr}^{-1}$ . Even for the longest records, particularly those within  $15^\circ$  of the equator in the Pacific Ocean, the large ENSO related interannual variability means that there is considerable uncertainty in the trends from individual gauges.

For the gauges with records longer than 24 years (but significantly shorter than 52 years), there are larger differences between the trends from individual tide gauges and the reconstructed trends. These differences are at least partly the result of poorly known vertical land motions and the large interannual variability. One notable issue was at Funafuti where the reconstruction gave a lower rate of sea-level rise than the tide-gauge record if no allowance is made for sinkage of the UHSLC tide gauge. When the trends from locations with greater than 24 yrs of data are averaged, the estimated rate of relative sea-level rise is  $1.0 \text{ mm yr}^{-1}$  from the tide-gauge data, slightly less than the  $1.3 \text{ mm yr}^{-1}$  from the reconstructions. After making the GIA and inverse barometer corrections, the corresponding rates of sea-level rise are  $1.5 \text{ mm yr}^{-1}$  for the observations and  $1.6 \text{ mm yr}^{-1}$  for the reconstructions, consistent with global average rates of sea-level rise. Unfortunately, there are no long records from island tide gauges in the Indian Ocean and it is necessary to rely on the reconstructions for information of sea-level change over the 1950 to 2001 period. Some support for the pattern of rise comes from thermal expansion data (Lombard et al., 2005) and geological data (Woodroffe, 2005).

For the six complete records from the Pacific Ocean, there is an increase in variance of the monthly sea-level data after 1970, particularly for the stations within  $15^\circ$  of the equator, for which the variance after 1970 is more than double the pre-1970 variance (commensurate with changes in the variability of the SOI index; Torrence and Webster, 1999). This increase in variance (if maintained at the new level into the future) together with a rise in the mean sea-level will result in an increase in the frequency of extreme events of a given magnitude and has important implications for the local impacts of sea-level rise.

The pattern of sea-level rise from the reconstructions (Fig. 6) is consistent with the trend to more frequent, persistent and intense ENSO events in the past 2 decades (Folland et al., 2001). The lowest estimated rates of sea-level rise over this 52 year period are close to zero south-west of the Maldives, consistent with geological data of low rates of sea-level rise in this region (Woodroffe, 2005). For the Maldives themselves, the estimated rate of sea-level rise over the 52 year period is close to  $1 \text{ mm yr}^{-1}$  and, in contrast to Mörner et al. (2004), we find that there is no indication of a fall in sea-level of 20 to 30 cm at any time in the last 30 yrs (which would imply a rate of fall of between 7 and  $10 \text{ mm yr}^{-1}$  over 30 yrs, and double that over the “1970s to early 1980s” specified by Mörner et al. (2004)). This drop in sea-level has also been shown to be inconsistent with geological data (Woodroffe, 2005; Kench et al., 2005). Our best estimate of the rate of relative sea-level rise at Funafuti is  $2 \pm 1 \text{ mm yr}^{-1}$ . Clearly sea level in this region is rising, and we expect the direct and indirect (e.g. increased frequency of extreme events) effects of this rise and the observed increase in the rate of rise (Church and White, 2006) will cause serious problems for the inhabitants of some of these islands during the 21st century.

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data, provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, is acquired from their Web site at <http://www.cdc.noaa.gov/>.

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