A Note on Relative Sea Level Change at Funafuti, Tuvalu

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Executive Summary

This document describes an analysis of long-term relative sea level change[1] at Funafuti, Tuvalu. It is based on data provided by the University of Hawaii Sea Level Centre (UHSLC) and the Australian National Tidal Facility (NTF), and covers the years 1978 to 2001 inclusive. Standard statistical techniques have been used to estimate the rate of change of sea level and its associated uncertainty.

A cautious estimate of present long-term relative sea level change at Funafuti, which uses all the data, is a rate of rise of **0.8 ± 1.9 mm/year**[2] relative to the land. This indicates that there is about a 68% probability of the rate of rise being between -1.1 and 2.7 mm/year.

A less cautious estimate, based on the rejection of data affected by El Niño / Southern Oscillation (ENSO) events, is a rate of rise of **1.2 ± 0.8 mm/year** relative to the land. This indicates that there is about a 68% probability of the rate of rise being between 0.4 and 2.0 mm/year.

Although these estimates of *relative* sea level change at Funafuti are not directly comparable with the IPCC estimate of *global average* sea level rise during the 20th century (1 to 2 mm/year; Church *et al.*, 2001), it is interesting to note that they are of similar magnitudes. For the rate of absolute sea level change at Tuvalu to lie within the range of global average sea level rise given by the IPCC, only modest constraints have to be applied to the vertical land motion at Tuvalu; the observations from Tuvalu are therefore not inconsistent with the IPCC estimate of global average sea level rise.

It is also shown that the uncertainty in sea level trend estimated from the data collected by NTF since 1993, using a modern acoustic tide gauge, is ±13.7 mm/year, indicating that this data set is presently of little value for the investigation of long-term sea level rise. The large uncertainty is caused mainly by the relative shortness of the record and the effect of ENSO-related events which occur every few years.

Even using the full 24 years of available data, the uncertainties in estimated trend are presently undesirably large. It is shown that, using the 'cautious' analysis (see above), a further 56 years of data would be required to reduce the uncertainty associated with environmental variability to, say, ±0.3 mm/year (30%, if the rate of rise is 1 mm/year). However, using the 'less cautious' analysis, only a further 15 years of data would be required to reduce this uncertainty to ±0.3 mm/year. Further consideration should therefore be given to the validity of the assumptions used in the 'less cautious' analysis, as it could reduce the required record length for a useful estimate of sea level rise by over 40 years.

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[1] See Footnote 4 (Section 1) for definitions.

[2] All uncertainty estimates are quoted here as ± 1 standard deviation.

1 Introduction

The sea level change at Tuvalu has recently been the subject of significant government and public interest, due to the low-lying nature of the islands, which rise only a few metres above sea level, and reports that flooding is becoming increasingly common. Future predictions for global average sea level rise during the 21st century lie in the range 0.09 to 0.88 m (Church *et al.*, 2001). This rise could have serious consequences for low-lying countries, and could be compounded by other possible effects of climate change, such as the change in intensity of extreme weather events. Rising sea level is also associated with an increase in the frequency of extreme events such as storm surges (Church *et al.*, 2001). It is therefore important that the best estimate of relative sea level change at Tuvalu, and its associated uncertainty, be made from the available data.

Tide gauge records for Funafuti are available since 1977, based mainly on an installation run by the University of Hawaii. In 1993 a modern Aquatrak acoustic gauge was installed at a nearby site by the Australian National Tidal Facility (NTF) as part of the AusAID-sponsored South Pacific Sea Level and Climate Monitoring Project. Two records have been considered here; they are denoted records 'A' and 'B'. Record A consists of annual averages of the 'historic' record, which is based on a number of different tide gauges, and which has been provided by the University of Hawaii Sea Level Center (UHSLC). Record B consists of annual averages of data collected by the NTF from their acoustic gauge since 1993. The part of Record A prior to 2000 was derived from the University of Hawaii gauge, while the remainder is from the NTF gauge. This latter part of Record A is essentially identical to Record B (except for round-off errors and differences in the height reference datum). Due to the changes in tide gauge (and possible datum shifts), records such as A are generally regarded as less reliable for long term estimates of sea level change than records from a single gauge, operated by one organisation.

From the point of view of accuracy of individual observations, Record B is believed to be superior, although, as shown later, it is presently too short to yield a useful estimate of long-term sea level change.

Sea level records show variability over a wide range of different time scales, including:

1. Tidal oscillations of periods which are predominantly in the approximate range 12 to 24 hours, but which also have components covering time scales of only a few hours to years.
2. 'Weather scale' phenomena, with time scales ranging from hours to weeks.
3. Seasonal variations.
4. Interannual variations such as the El Niño / Southern Oscillation (ENSO), which occur (very roughly) every 4 to 6 years.
5. Changes in climate over periods of tens of years to geological times scales.

In order to estimate any climate-related trend in sea level (i.e. (5), above), other variations are regarded as 'noise' and are removed from the original data, generally either by tidal analysis or by time-averaging. This unwanted 'noise' is a serious problem and dictates that long records are needed for the meaningful estimation of long-term sea level change. Douglas (2001) argued that records of at least 50 to 80 years duration may be required. Shorter records will undoubtedly yield rates of long-term sea level change that are contaminated by unwanted noise, and it is important that any such results are qualified with an appropriate estimate of the probable uncertainty.

Probably the most widely quoted estimates of long-term sea level change at Funafuti have been made by Mitchell *et al.* (2000) and by the NTF (2002). In particular, the NTF (2002) reported:

> *As at February 2002, based on the short-term sea level rise analyses, performed by the National Tidal Facility Australia, for the nearly nine years of data return show a rate of +0.9 mm per year.*

and:

> *The historical record from 1978 through 1999 indicated a sea level rise of 0.07 mm per year.*

These results, which are based on quite short records and for which no uncertainty estimates are provided, have unfortunately been quoted out of context and without appropriate qualification. For example, the 'greenhouse skeptic' website 'Still Waiting for Greenhouse' (`http://www.john-daly.com/`) made the statement (April, 2002) that:

> *Now the National Tidal Facility, based in Adelaide, Australia, has dismissed the Tuvalu claims as unfounded. They have maintained accurate monitoring of sea level at Tuvalu. According to their latest news release on the issue, 'Sea Level in Tuvalu: Its Present State', the NTF concludes 'The historical record from 1978 through 1999 indicated a sea level rise of 0.07 mm per year.' This compares with the IPCC*[3] *claim of 1 - 2.5 mm/yr for the world as a whole, indicating the IPCC claim is based on faulty modelling.*

Quite apart from the fallacy in suggesting that observations from a single site can cast doubt on a global average value, the above statement contains no qualification concerning the relatively short length of the record, nor of the probable uncertainty in the estimate. The purpose of this document is to provide values for the long-term relative sea level change[4] at Funafuti, Tuvalu, with appropriate estimates of uncertainty, using standard statistical analyses of publicly available data.

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[3] The 'IPCC' refers to the Intergovernmental Panel on Climate Change.

[4] 'Long-term' refers to time scales that are of interest in climate change. For example, present estimates of past and future climate change made by the Intergovernmental Panel on Climate Change, relate to changes over the 20th and 21st century, respectively. 'Relative sea level change' is defined as the change in sea level relative to the local land. It is the change that is measured by a tide gauge. It differs from the *absolute* sea level change (i.e. the change relative to some fixed Earth coordinate system) because of vertical motion of the land, which may be caused by tectonics or by the response of the Earth's crust to the weight of overlying ice or water.

2 Data

2.1 Timing

Sea level data for this study were derived from two sources: from the UHSLC and from the NTF. These data were recorded every calendar month, which can present difficulties for analyses, given the difference in the lengths of the months, and (to a lesser extent) the difference between leap years and 'normal years'. For the present work, 'years' are defined as of equal length (365.25 days), with the year denoted '1977' starting at 00:00 on 1 January 1977 (which is prior to any sea level data for Funafuti). '1977' is therefore defined as the 365.25-day period starting at the beginning of the conventional 1977. '1978' is the 365.25-day period starting at 06:00 on 1 January 1978, and so on. For the purpose of understanding the results presented here, the years as defined here are practically equivalent to conventional calendar years.

Annual data were derived by trapezoidal integration of monthly data over each of these nominal 'years'.

2.2 Uncertainty

For most of the results quoted in this document, uncertainty is quoted as ± 1 standard deviation. For data that that is distributed by a normal (or Gaussian) law, there is a 68% probability of the 'true' value being within this range.

In some cases it is desirable to quote a range, which includes the 'true' value to a higher degree of certainty. It is conventional to define this range by limits which are ± 2 standard deviations; for data that is distributed by a normal law, there is a 95% probability of the 'true' value being within this range. In this document, limits of uncertainty are provided for the estimate of vertical movement of the University of Hawaii tide gauge, and for comparisons of the Tuvalu results with estimates of the rise of global average sea level.

2.3 Record A

Historical data for Funafuti (called Record '$\mathrm{A_m}$', to denote monthly data; see Section 1) was obtained from the UHSLC website:

`ftp://ilikai.soest.hawaii.edu/rqds/pacific/monthly/`

on 5 August 2002.

File `m025a.dat` was the actual data, while file `qa025a.dmt` provided documentation describing the data. The data contained average sea level values for each calendar month from November 1977 to December 2001. There were several data gaps as shown in Table 1.

Year(s)	Missing months
1979	February
1979	April
1979	July-August
1980	March
1980/1981	December-February
1981	April
1981	June
1983	March

Table 1: Missing data in Record $\mathrm{A_m}$.

The longest gap was therefore of three months. The data, with the time-averaged level removed, is shown in Figure 1. Annual and semi-annual sine waves were removed by linear regression, in order to reduce the seasonal signal. Annual values were then obtained by trapezoidal integration within each year. The resultant data with the time-averaged level removed (Record A), is shown in Figure 2.

2.4 Records A2 and A4

The analyses of Section 3 are primarily statistical. One assumption used in the estimation of uncertainties is that individual values are independent. Inspection of Figure 2 suggests that this is not the case for annual data, in which adjacent values appear quite highly correlated. Subsidiary data sets were therefore generated by averaging adjacent values in order to increase the level of independence. Figure 3 shows two-year averages of Record A (called 'A2') and figure 4 shows four-year averages of Record A (called 'A4'). Record A2 has less correlation between adjacent points, while Record A4 appears to be composed of independent values. The analyses of Section 3 were performed on Records A, A2 and A4; however, the resultant trends and uncertainty estimates differed little.

2.5 Record B

The acoustic tide gauge data (called Record '$\mathrm{B_m}$', to denote monthly data; see Section 1) was obtained from the NTF website:

`http://www.ntf.flinders.edu.au/TEXT/WOCE/pacific_means.html`

on 13 May 2002.

The filename was called `tvSL.bef` and contained average sea level values for each calendar month from March 1993 to March 2002. There were two data gaps, for October 1993 and July 1997. The data, with the time-averaged level removed, is shown in Figure 5. Annual and semi-annual sine waves were removed by linear regression, in order to reduce the seasonal signal. Annual values were then obtained by trapezoidal integration within each year. The resultant data with the time-averaged level removed (Record B), is shown in Figure 6.

2.6 Vertical Stability of the Tide Gauges

There is some uncertainty in the vertical stability of the University of Hawaii tide gauge. Figure 7 shows the difference between the Records $\mathrm{A_m}$ and $\mathrm{B_m}$ (i.e. the original monthly data) during the period when there is simultaneous data. Ideally, the difference should not change with time. After 1 January 2000, Record $\mathrm{A_m}$ was derived from data from the NTF gauge, by applying a constant offset of -0.772 m (from the documentation accompanying the UHSLC data). Figure 7 illustrates this offset correctly, given an acceptable rounding error of ±2 mm. In mid-1994, the difference exhibits an excursion of about 0.02 m, of unknown origin, and in March 1997, the difference exhibits a step of about 0.017 m, which may be due to a small subsidence of the UHSLC gauge related to abnormally high winds of greater than 20 $\mathrm{ms^{-1}}$ on 15 March (NTF, 1997). This step appears to settle during the rest of 1997 and 1998, resulting in an overall jump of about 0.01 m between 1996 and 1999. It appears that this jump has not been corrected for, and that the NTF data (Record $\mathrm{B_m}$) has simply been matched to the data for Record $\mathrm{A_m}$ at the start of 2000. There may therefore be a spurious jump of about 0.01 m in Record $\mathrm{A_m}$ between 1996 and 1999. A less probable alternative (since emergence is less likely than subsidence) is that Record $\mathrm{B_m}$ could have suffered a jump in the opposite direction.

Figure 8 shows results of levelling surveys carried out by the NTF (NTF, undated; NTF, 2000). The curves represent levels relative to a reference benchmark (denoted BM22 in the NTF documents) that is presumed to be stably located. The curves are also plotted so that their vertical position corresponds to zero in March 1993 (the first data point). The upper curve, representing the benchmark for the NTF gauge (denoted TUV20 in the NTF documents), indicates that this gauge has been vertically stable to ±1 mm from 1993 to 2000. However, the benchmark for the UHSLC gauge (denoted UH1 in the NTF documents) appears to have subsided by more than 0.012 m over that period. Interestingly, there appears to be no jump of 0.01 to 0.017 m in either record during 1997, so the step observed at this time in Figure 7 remains a mystery. The subsidence between 1993 and 1994 for the UHSLC gauge appears to be excessive compared with the rate of later subsidence, so it may be that the first data point is erroneous. The steeper trend line (-1.5 mm/year) results from a linear regression on all the data points for the UHSLC gauge. The other trend line (-1.0 mm/year) is again based on data for the UHSLC gauge, but omitting the first point.

In summary, it appears that during the period 1993 to 2000 (a period of 7 years, or less than a third of the length of Record $\mathrm{A_m}$), the UHSLC gauge suffered subsidence at a rate of between 1 and 1.5 mm/year. Two extreme cases are considered:

1. The subsidence was zero for the first 15 years (1978-1992), 1.0 mm/year for the next 7 years (1993-1999) and zero for the last 2 years (2000-2001, when the data in

Record $\mathrm{A_m}$ was derived from the (vertically stable) NTF gauge). Over the 24-year period of Record $\mathrm{A_m}$, this averages out to a trend of about 0.3 mm/year.

2. The subsidence was 2.5 mm/year for the first 15 years (1978-1992), 1.5 mm/year for the next 7 years (1993-1999) and zero for the last 2 years (2000-2001). Over the 24-year period of Record $\mathrm{A_m}$, this averages out to a trend of about 2.2 mm/year.

The limits of the rate of subsidence for the UHSLC gauge are therefore about 0.3 to 2.2 mm/year over the period 1978-2001. Since the uncertainties in this document are expressed as ± 1 standard deviation, and since limits of uncertainty are roughly ± 2 standard deviations (Section 2.2), the rate of subsidence is therefore approximately **1.2 ± 0.5 mm/year**. Sea level rise estimates from Record $\mathrm{A_m}$ should therefore be *reduced* by this rate in order to obtain rates of sea level rise relative to the land at Tuvalu.

3 Analyses

3.1 Introduction

Four analyses were performed on Records A, A2 and A4 (Sections 2.3 and 2.4). The first two analyses are quite qualitative, but are included here as a way of improving understanding of the data. The second two provide the main estimates of this report and involve standard linear regression, accompanied by estimates of the uncertainty of the results. The regression analysis was also performed on Record B (Section 2.5), in order to provide an indication of the expected uncertainty from a record of only eight years duration.

3.2 Analysis I

Inspection of Figure 2 reveals an apparently upward trend, confined to the data points lying between heights of about 0 and 0.1 m, punctuated by sharp falls in 1983, 1987, 1992 and 1998. These negative excursions are associated with ENSO events, which are normally characterised by the ‘Southern Oscillation Index’ (SOI) (see annual values of SOI in Figure 9; CRU, 2002). If we ignore these events, it is tempting to draw a line by eye through the remaining points, as shown in Figure 10. The superimposed line has a slope of 2.5 mm/year. Allowing for subsidence of the UHSLC gauge of 1.2 mm/year (Section 2.6), this suggests a rate of sea level rise of 1.3 mm/year relative to the land.

One way of examining the trend in the maximum excursions of the annual data is to apply a ‘maximum’ filter. This is similar to a running mean, except that the maximum value of the data is selected, rather than the average. Therefore, for a four-year maximum filter, the annual data points for 1978 to 1981 are first examined and the point with the maximum height is selected and plotted. Next, the annual data points for 1979 to 1982 are examined and again the maximum value is selected and plotted. This process is repeated for the whole record. The resultant set of points are those that have a maximum height in any four-year span of data. The results for a four-year maximum filter are shown in Figure 11. The superimposed line has a slope of 2.2 mm/year. Allowing for subsidence of the UHSLC gauge of 1.2 mm/year, this suggests a rate of sea level rise of 1.0 mm/year relative to the land. The results using a two-year maximum filter are similar but rather more 'noisy'.

These estimates of sea level change are clearly very approximate, involving a subjective fitting procedure and no estimate of uncertainty. They are introduced here solely to illustrate the contaminating effect of SOI events, and the fact that, if we neglect such events, an upward trend in sea level is quite clear.

3.3 Analysis II

Record A consists of 24 annual average values covering the period 1978 to 2001, inclusive. One simple way of estimating the trend in a time series is to divide the time series into two parts about the mid-point, to take the difference of the average of each part, and to divide the result by half the length of the record (since each average level may be taken to apply to the middle of its respective part). This is shown schematically in Figure 12. The results are summarised in Table 2, where the time-averaged level has first been removed from Record A.

In summary, the average sea level during 1990 to 2001 was 0.0274 m higher than it was during 1978 to 1989, representing a rate of rise of 2.3 mm/year. Allowing for subsidence of the UHSLC gauge of 1.2 mm/year, this suggests a rate of sea level rise of 1.1 mm/year relative to the land. This simple analysis does not, however, provide an estimate of the uncertainty in the rate of rise. A formal analysis of the trend, with associated estimate of uncertainty, is described in the following Sections.

Calculation	Result
Average level 1978 to 1989	-0.0137 m
Average level 1990 to 2001	0.0137 m
Difference in average levels (1990 to 2001)-(1978 to 1989)	0.0274 m
Average rate of rise	2.3 mm/year

Table 2: Results of Analysis II applied to Record A

3.4 Analysis III

3.4.1 Introduction

Linear regression is the most common way of estimating a trend, and its associated uncertainty (e.g. Press *et al.*, 1986). The result is a 'best fit' straight line through the data points (similar to the lines drawn in Figures 10 and 11, but objectively derived), and estimates of the uncertainty in the constants defining that straight line. The uncertainty analysis, in its simplest form (as used here) assumes that each data sample has an independent error (in this case, we regard the deviation from a straight line fit as being the 'error'). The analysis has been applied to Record B, and in various forms, to Records A, A2 and A4.

3.4.2 Record B

Linear regression was applied to Record B, the annually averaged sea level data shown in Figure 6. This covered the period 1994 to 2001, inclusive. The resultant trend is $\mathbf{-1.0 \pm 13.7}$ **mm/year**. The trend is similar (given the size of the uncertainty) to the '+0.9 mm/year' reported by the NTF (2002) for a slightly longer span of data (see Section 1). However, the large uncertainty of ±13.7 mm/year, which results from the relative shortness of the record, indicates that this data set is presently virtually useless for estimating long-term sea level change at Funafuti.

3.4.3 Record B, Truncated at Specific Years

It is interesting to investigate the trends and uncertainties that would have been derived from Record B if it were terminated earlier. Figure 13 shows the results of analysing Record B, terminated at different years (in this case, each year in the range 1996 to 2001). For example, the data point at '1998' represents the results obtained by using all of Record B up to and including 1998, but rejecting all subsequent data. It should be noted that the uncertainties shown in Figure 13 are only approximate, due to the relative short length of the record (for example, a record terminated prior to 1998 would contain no ENSO event) and the fact that adjacent annual values appear highly correlated. However, it is clear from the differences of the estimates since 1998 that the uncertainty is typically ±10 mm/year. This large uncertainty is illustrated by the rate of sea level rise of -12.8 mm/year which was estimated by the NTF for the period early-1993 to 1999 using this same data set (Mitchell *et al.*, 2000). For a slightly shorter period (1994 to 1999), Figure 13 indicates a trend of -20.9 ± 22.3 mm/year.

3.4.4 Records A, A2, A4

Linear regression was applied to Records A (annual average), A2 (two-year average) and A4 (four-year average). The results are summarised in Table 3. Inspection of Figures 2 to 4 show that there is significant correlation between adjacent data points in Figures 2 and 3, while there is little correlation evident in Figure 4. Record A4 (four-year averaged data) therefore probably provides the best estimate of the uncertainty in the trend (see Section 3.4.1). The favoured estimate of trend and associated uncertainty for these records is therefore 2.0 ± 1.8 mm/year (i.e. as derived for Record A4), although it should be noted that the results are very similar in all three cases. Allowing for subsidence of the UHSLC gauge of 1.2 ± 0.5 mm/year and combining the uncertainties appropriately, this yields a rate of sea level rise of **0.8 ± 1.9 mm/year** relative to the land.

Record	Averaging period (years)	Data shown in Figure	Sea level trend (mm/year)
A	1	1	2.2 ± 2.3
A2	2	2	2.2 ± 2.1
A4	4	3	2.0 ± 1.8

Table 3: Results of Analysis III applied to Records A, A2 and A4.

3.4.5 Record A, Truncated at Specific Years

Figure 14 shows the results of analysing Record A, terminated at different years (in this case, each year in the range 1991 to 2001), as described in Section 3.4.3. The figure indicates why the NTF (2002) got a result (0.07 mm/year; see Section 1) that was apparently so different from the trends found in the previous Section. The record analysed by the NTF finished at the end of 1998 (Bill Mitchell, NTF, pers. comm.). It is seen from Figure 1 that 1998 exhibited a very low sea level, probably due to the influence of ENSO. Terminating the record at this point leads to a greatly reduced apparent trend. The result for 2001 is the value for 'A' given in Table 3. The value for 1998 is 0.0 ± 2.9 mm/year, which is approximately the same as the NTF's estimate of 0.07 mm/year. The small discrepancy is probably due to different starting times for the record (the analysis presented here starts at the beginning of 1978, while the historic UHSLC data starts in November 1977), and minor differences in the analysis procedure.

It should be noted that the estimates of trends and uncertainties, obtained from records terminated at years 1991 to 2001 (Figure 14), encompass, to within ± 1 standard deviation, the range -0.1 to 2.9 mm/year. This range brackets the present 'best' estimates of 2.0 to 2.2 mm/year (Table 3), and also the rate of rise estimated by the NTF (2002) of 0.07 mm/year. Allowing for subsidence of the UHSLC gauge of 1.2 mm/year, this range becomes -1.3 to 1.7 mm/year, relative to the land.

3.5 Analysis IV

Figures 2 and 10 suggest that there is an overall upward trend in sea level at Funafuti, punctuated by strong negative excursions in 1983, 1987, 1992 and 1998, which are probably related to ENSO events. It is these excursions that are the major source of uncertainty in the estimates of trends so far described in this document. This uncertainty would be reduced if these minima were regarded as 'outliers' and rejected from the least squares analysis. There are two possible reason for doing this:

1. It is possible that the negative excursions are independent of the sea level trend and may be regarded as random (large) events superimposed on a steady rate of change.

2. The periods between these negative excursions last from 3 to 4 years. From the point of view of the environmental effect on Tuvalu, the negative excursions in no way compensate for an increasing sea level between these excursions (i.e. ‘unflooding’ a region does not compensate for any previous flooding). It is therefore appropriate to analyse for the trend in the upper ‘envelope’ of the sea level record shown in Figure 2.

There is a standard and simple technique for removing outliers in a linear regression analysis. Firstly, an analysis is performed with all the data, and any data points that fall more than a prescribed distance (here called the ‘tolerance’) from the regression line are rejected. The regression is then repeated on the reduced set of data, yielding a rather different line of best fit. The rejection process is then repeated, starting with the full data set, so as to obtain a new ‘reduced’ data set, on which a regression analysis is again performed. The whole process is repeated until the ‘reduced’ data set remains unchanged (i.e. a set of data has been found such that all points in the set fall within the defined tolerance of its regression line, and all other points fall outside the defined tolerance).

Figures 15 and 16 shows the number of annual data points accepted and the estimated sea level rise, respectively, as a function of the prescribed tolerance. When the tolerance is greater than or equal to 0.225 m, all 24 annual data points are accepted and the result is the same as that shown for Record A in Table 3. As the tolerance is reduced, so are the numbers of data points accepted (Figure 15), until, when the tolerance becomes less than 0.05 m, the number of accepted points falls dramatically. Figure 16 shows that the uncertainty in the trend estimation reduces as the tolerance is decreased and less data points are accepted. The rate of rise has a reasonably stable value for tolerance greater than or equal to 0.05 m. A suitable choice of tolerance appears to be 0.05 m, for which 18 annual values are accepted and the rate of rise is 2.4 ± 0.6 mm/year. The rejected years were in this case 1983, 1984, 1987, 1992, 1993 and 1998. It should be noted that this analysis was based only on the annual data set (A), which shows significant correlation between adjacent data points. The two-year and four-year averaged data sets (A2 and A4) were not used for two reasons: firstly the temporal averaging tends to mask the ENSO ‘outliers’, and secondly, Section 3.4.4 indicates that the choice of A, A2 or A4 does not greatly alter the results.

Allowing for subsidence of the UHSLC gauge of 1.2 ± 0.5 mm/year and combining the uncertainties appropriately, this yields a rate of sea level rise of **$\mathbf{1.2 \pm 0.8}$ mm/year** relative to the land.

4 Comparison with the IPCC Estimate of Global Average Sea Level Rise

The absolute rate of sea level change (V_A) is related to the relative rate of sea level change (V_R) and the vertical motion of the land (V_L) by

$$V_A = V_R + V_L \tag{1}$$

where all motions are defined as positive in the upward direction.

Given a range of the rate of absolute sea level change (V_A^{min} to V_A^{max}) and a range of the rate of relative sea level change (V_R^{min} to V_R^{max}), Equation (1) may be used to derive limits on the vertical motion of the land (V_L^{min} to V_L^{max}):

$$V_L^{min} = V_A^{min} - V_R^{max} \tag{2}$$

and

$$V_L^{max} = V_A^{max} - V_R^{min} \tag{3}$$

The IPCC Third Assessment Report stated (Church *et al.*, 2001):

On the basis of the published literature, we therefore cannot rule out an average rate of sea level rise of as little as 1.0 mm/yr during the 20th century. For the upper bound, we adopt a limit of 2.0 mm/yr, which includes all recent global estimates with some allowance for systematic uncertainty.

These figures relate to the sea level change caused by an increase in volume of the ocean, both by thermal expansion and by the addition of water (e.g. through melting of glacial ice). They are not directly comparable with the relative sea level change observed at Tuvalu, for three main reasons. Firstly, sea level rise is undoubtedly not constant over the world's ocean. Secondly, relative sea level change is affected by any vertical motion of the land. Thirdly, the IPCC estimate relates to the average rate of rise over the 20th century, which should be *smaller* than the present rate if sea level is accelerating (the expectation for the present century as global warming progresses; Church *et al.*, 2001). However, it is still useful to compare the IPCC estimate with the results derived for Tuvalu. Since the IPCC estimate is expressed in terms of a pair of limits of uncertainty (i.e. a range), then the results for Tuvalu should be expressed in a similar way. It is conventional to define limits of uncertainty as ± 2 standard deviations (Section 2.2); estimates, derived in this way, of the range of relative sea level rise for Analyses III and IV are shown Table 4. Also shown in Table 4 is the IPCC estimate of global average sea level rise, which is here assumed to correspond to the rate of absolute sea level rise at Tuvalu, and the resultant limits on vertical land motion, derived from Equations (2) and (3). The narrowest limits on vertical land motion are for Analysis IV (-1.8 to 2.4 mm/year).

In summary, if the IPCC estimate of global average sea level rise (Church *et al.*, 2001) were to apply to Tuvalu, then the observations of relative sea level change at Tuvalu constrain the vertical land motion to lie in the range -1.8 to 2.4 mm/year. Because it is quite conceivable that the actual vertical land motion lies within this range (e.g. the simulations of glacial isostatic adjustment of Peltier, 2001), the observations from Tuvalu are not inconsistent with the IPCC estimate of global average sea level rise.

Analysis	Range of V_R (mm/year)		Range of V_A (mm/year)		Range of V_L (mm/year)	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
III	-3.0	4.6	1.0	2.0	-3.6	5.0
IV	-0.4	2.8	1.0	2.0	-1.8	2.4

Table 4: Limits of uncertainty of the rate of relative sea level change, the rate of absolute sea level change (assuming that the IPCC global average estimate (Church *et al.*, 2001) applies) and the rate of vertical land motion (calculated according to Equations (2) and (3)).

5 Summary

Two sets of sea level data from Funafuti, Tuvalu, were initially procured, one from UHSLC and the other from the NTF. The longer one, from UHSLC, was used to derive annual average sea levels for the period 1978 to 2001, inclusive. Subsidiary data sets consisting of two-year and four-year averages of the annual data were generated. These formed the basis of four analyses. The two initial analyses (I and II) are included only as an introduction to the data set and the results should be regarded as indicative only. The other analyses (III and IV) use linear regression to estimate the long-term trend in sea level and its associated uncertainty. Analysis III was the more cautious approach, which used all the data, while Analysis IV was less cautious, rejecting data associated with ENSO and reducing the apparent uncertainty in the trend estimation.

There appears to be subsidence of the UHSLC gauge at a rate of approximately $\mathbf{1.2 \pm 0.5}$ **mm/year**. The following estimates of sea level rise relative to the land have therefore been adjusted accordingly.

Analysis I (Section 3.2) provided simple subjective fits of linear trends to the non-ENSO part of the annual data, resulting in estimated rates of rise of 1.0 and 1.3 mm/year relative to the land.

Analysis II (Section 3.3) derived an estimate of sea level rise from the difference between the average sea levels for the periods 1978 to 1989, and 1990 to 2001. The resulting estimate of sea level rise, after adjustment for subsidence of the UHSLC gauge, is 1.1 mm/year relative to the land.

Analysis III (Section 3.4) used all the data, and provided estimates of the rate of rise for annual, two-year and four-year averages of the sea level record. The result from the four-year averaged data is deemed the most appropriate, yielding a rate of rise, after adjustment for subsidence of the UHSLC gauge, of $\mathbf{0.8 \pm 1.9}$ **mm/year** relative to the land.

Analysis IV (Section 3.5) involved a progressive rejection of annual data that were regarded as ‘outliers’. The most appropriate estimate was deemed to be based on the rejection of 6 annual data points associated with ENSO events, and yielded a rate of rise, after adjustment for subsidence of the UHSLC gauge, of $\mathbf{1.2 \pm 0.8}$ **mm/year** relative to the land.

In addition, a regression analysis was performed on data collected by the NTF since 1993, using a modern acoustic tide gauge. The estimated uncertainty in the trend was ±13.7 mm/year, indicating that this data set is presently of little value for the investigation of long-term sea level rise. The large uncertainty is caused mainly by the relative shortness of the record.

The most useful results of this work are those from Analyses III and IV, which indicate values for long-term sea level rise of 0.8 and 1.2 mm/year relative to the land, with rather large uncertainties. Analysis III indicates that there is about a 68% probability of the rate of rise being between -1.1 and 2.7 mm/year. Analysis IV, which relies on the assumption that it is permissible to reject the large negative excursions in sea level associated with ENSO, indicates about a 68% probability of the rate of rise being between 0.4 and 2.0 mm/year.

The IPCC has estimated that the global average sea level rise during the 20th century was 1 to 2 mm/year (Church *et al.*, 2001). While these figures are not directly comparable with the relative sea level change observed at Tuvalu, it is interesting to note that they are of comparable magnitudes. If it is assumed that the rate of absolute sea level change at Tuvalu *is* within the range of global average sea level rise given by the IPCC, then the vertical land motion at Tuvalu is constrained to lie in the range -1.8 to 2.4 mm/year; since this is quite conceivable, the observations from Tuvalu are not inconsistent with the IPCC estimate of global average sea level rise.

More accurate estimates of sea level change at Funafuti will have to wait until a longer span of data has been collected. It is important that a continuing record of sea level be collected, for three reasons. Firstly, Douglas (2001) has argued that records of at least 50 to 80 years duration may be required to yield robust estimates of sea level rise at a given site. Secondly, there are undoubtedly problems associated with the pre-1993 sea level records from Funafuti (for example, those related to subsidence of the UHSLC gauge and to old technology); a longer data record would contain a larger proportion of (higher quality) data collected by the NTF using their modern acoustic tide gauge. Thirdly, sea level rise is expected to accelerate during the present century (Church *et al.*, 2001); the determination of such an acceleration requires a significantly longer record than that required for the determination of a constant rate of rise. So, how long need the record at Funafuti be in order to estimate the present average sea level rise with reasonable accuracy, given what we already know about variations in sea level at the site? On the assumption that the perturbations to sea level are randomly distributed, it can be shown that the uncertainty in the estimated rate of sea level rise decreases as $L^{-3/2}$, where L is the length of the record. Figure 17 shows projected uncertainties in the estimated rate of rise for various record length (ignoring any uncertainty in the subsidence of the UHSLC gauge), based on the results of Analyses III and IV. The Figure shows that, in order to reduce the uncertainty to, say, 0.3 mm/year (30%, if the rate of rise is 1 mm/year), we have to wait until 2057 using Analysis III and until 2016 using Analysis IV. There is therefore a very good reason why it would be beneficial to further consider the validity of assumptions similar to those used to justify Analysis IV: it could reduce the required record length for a useful estimate of sea level rise by over 40 years.

6 Acknowledgements

Historic sea level data were provided by the University of Hawaii Sea Level Centre. Sea levels for Tuvalu were supplied by the National Tidal Facility, The Flinders University of South Australia, Copyright reserved. Philip Woodworth of the Permanent Service for Mean Sea Level provided valuable comments on an earlier version of this manuscript. Richard Coleman advised on aspects of the levelling surveys.

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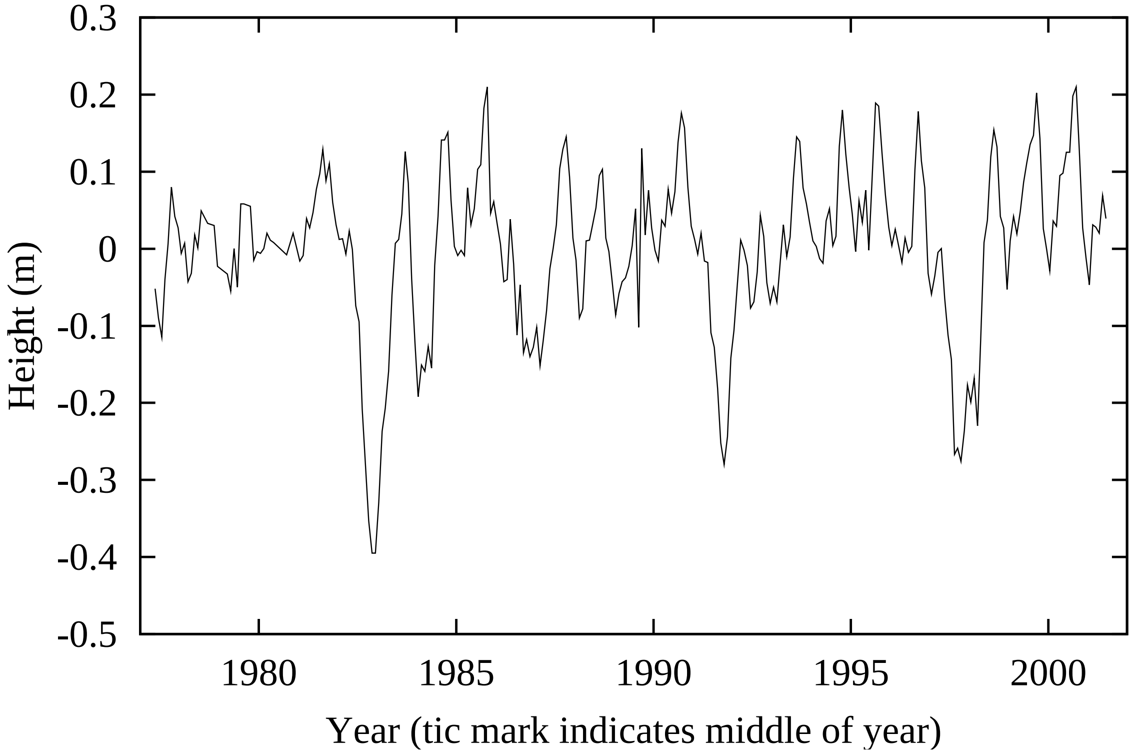

Figure 1: Monthly sea level data from UHSLC (Record A_m), with the time-averaged level removed.

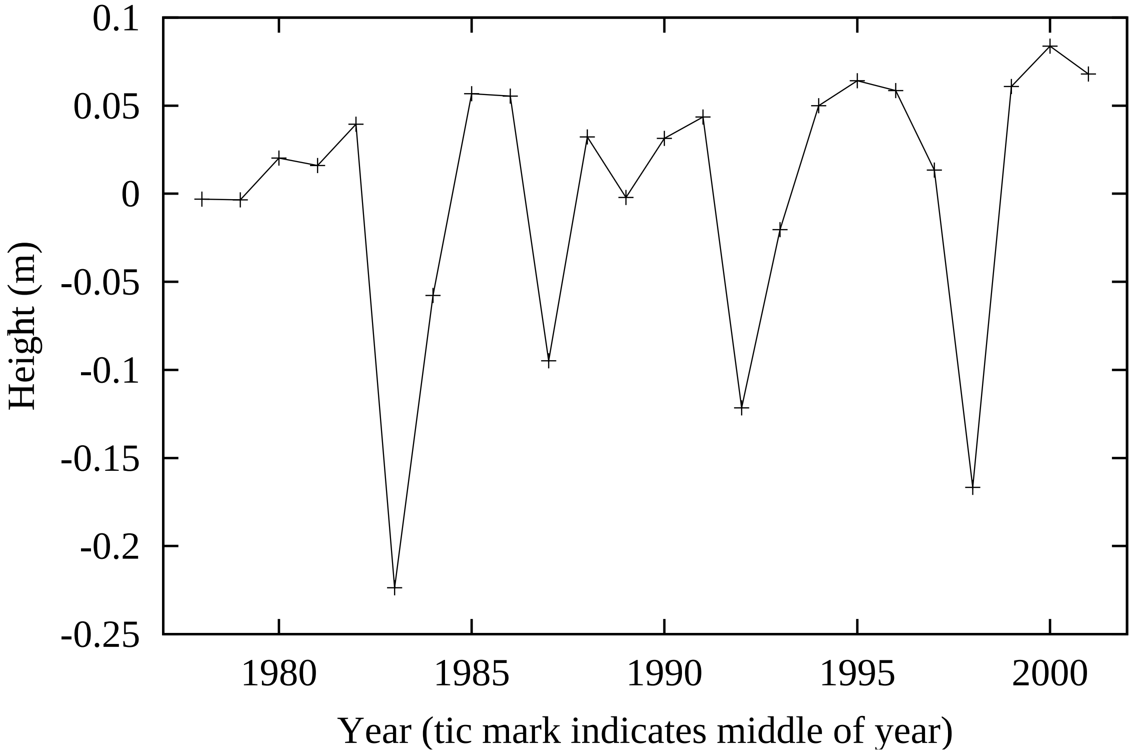

Figure 2: Annual sea level data from UHSLC (Record A), with the time-averaged level removed.

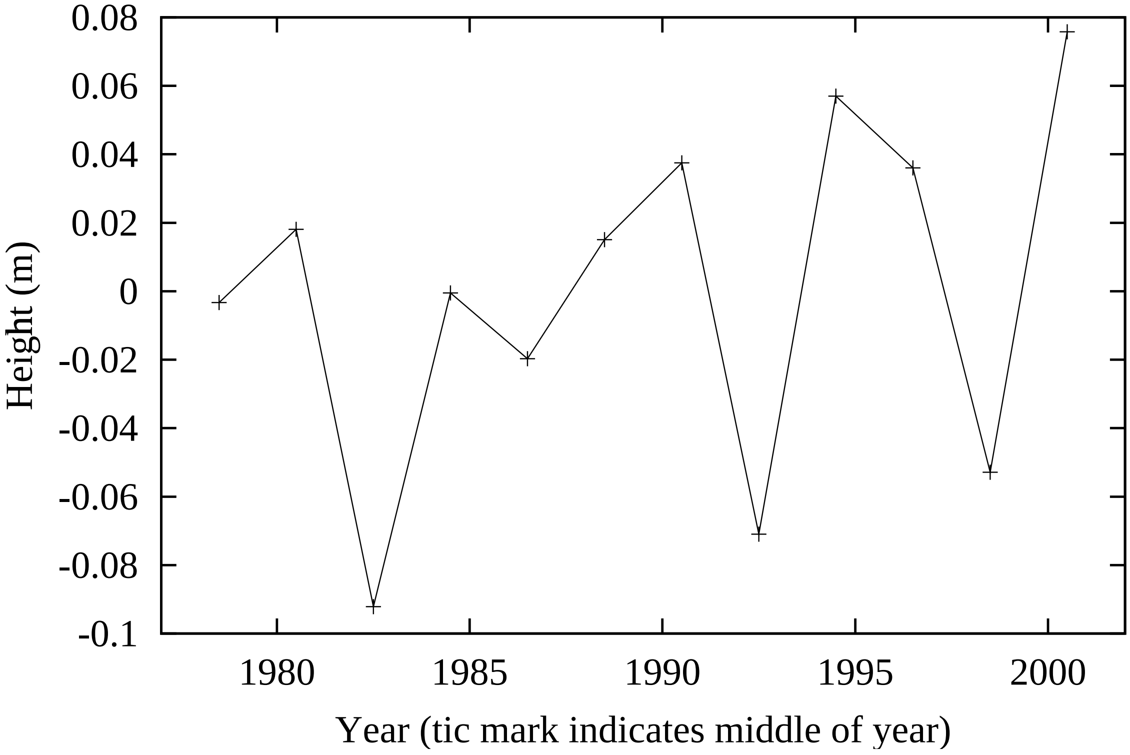

Figure 3: Two-year averages of sea level data from UHSLC (Record A2), with the time-averaged level removed.

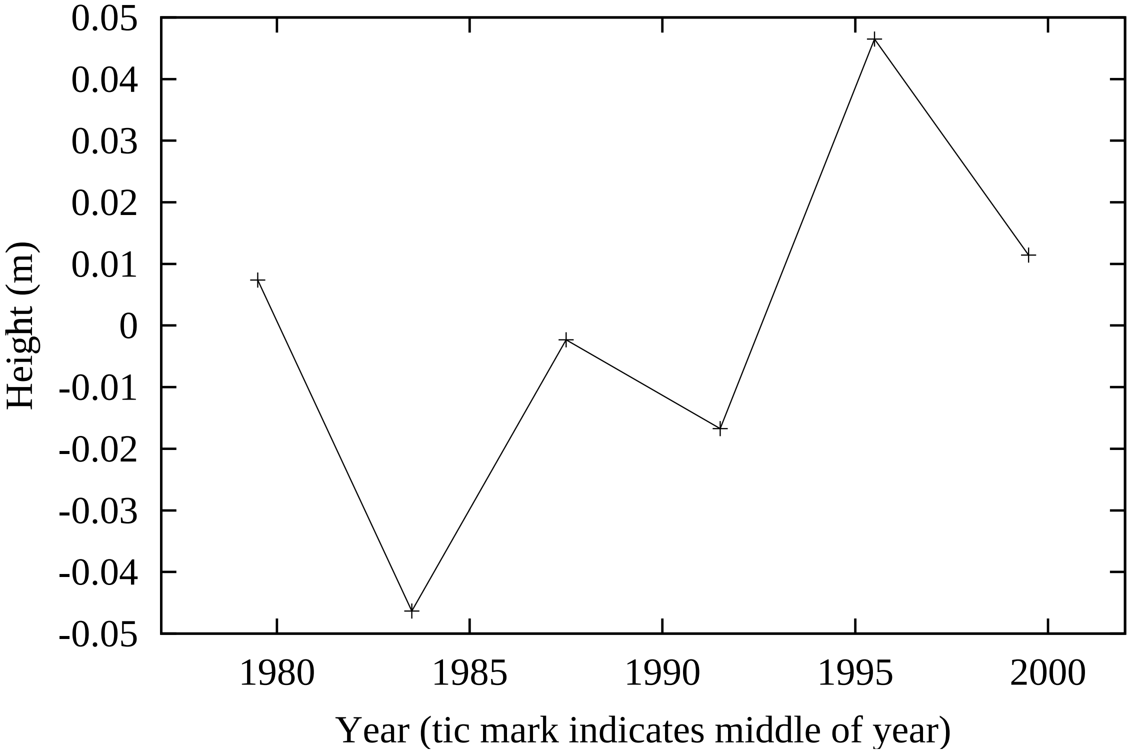

Figure 4: Four-year averages of sea level data from UHSLC (Record A4), with the time-averaged level removed.

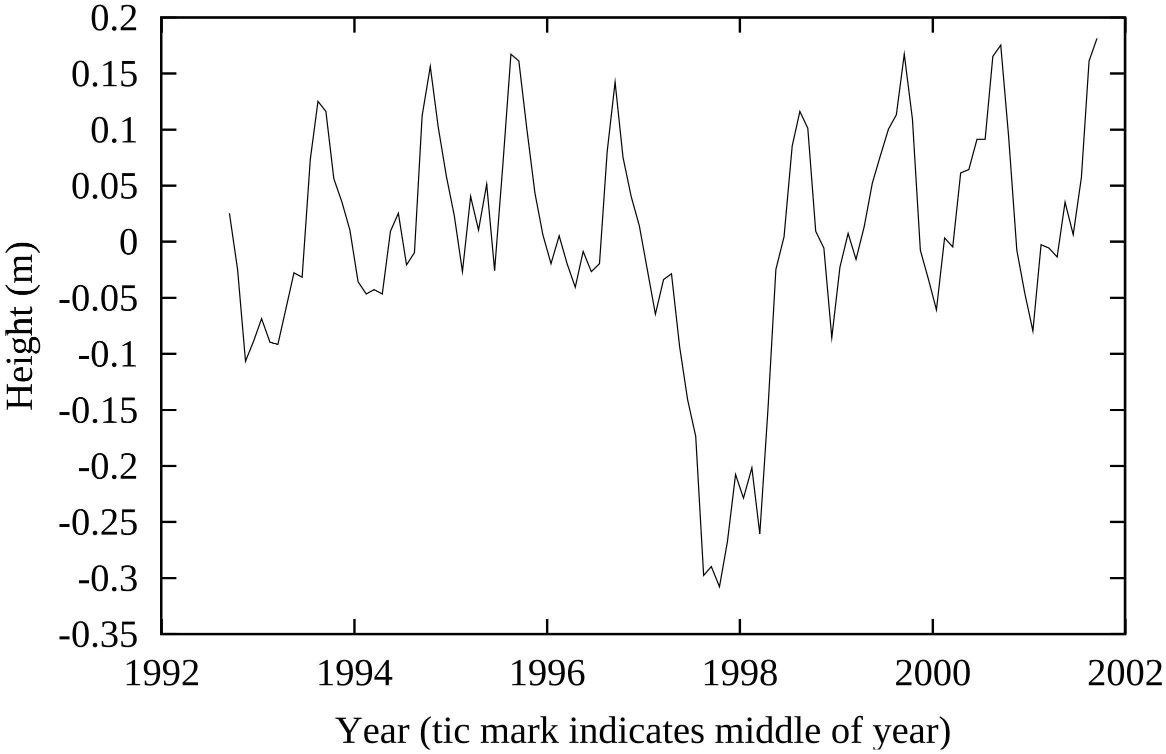

Figure 5: Monthly sea level data from the NTF (Record B_m), with the time-averaged level removed.

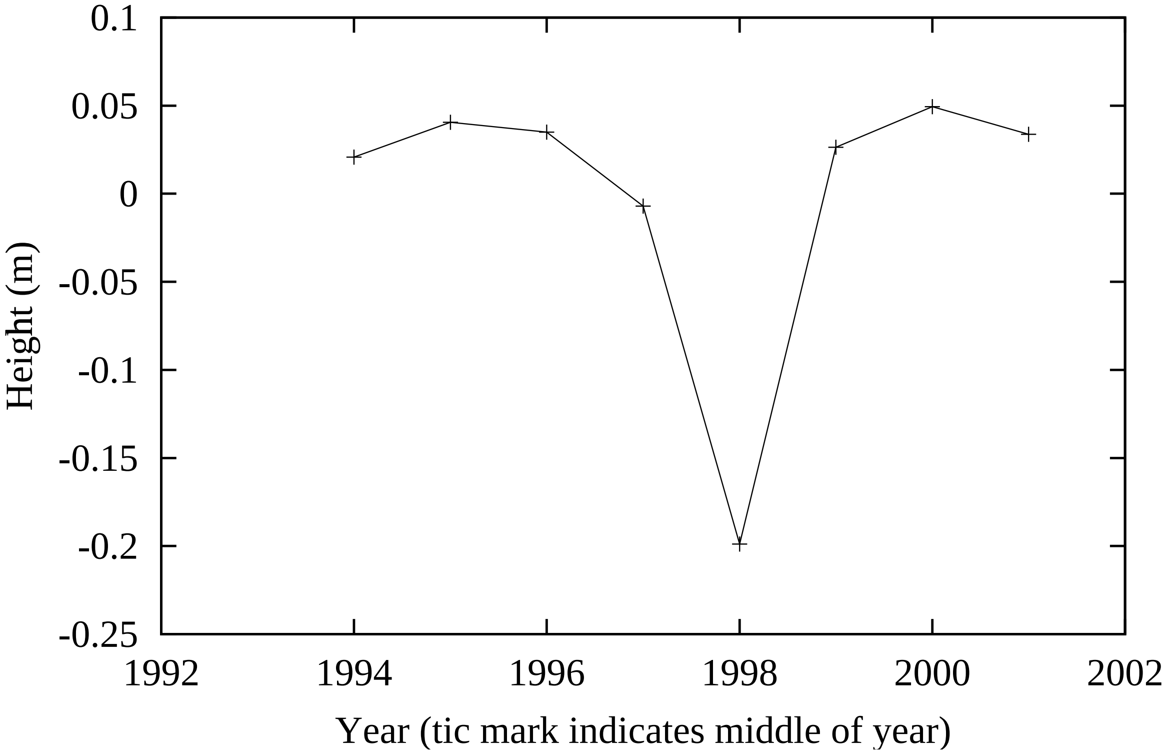

Figure 6: Annual sea level data from the NTF (Record B), with the time-averaged level removed.

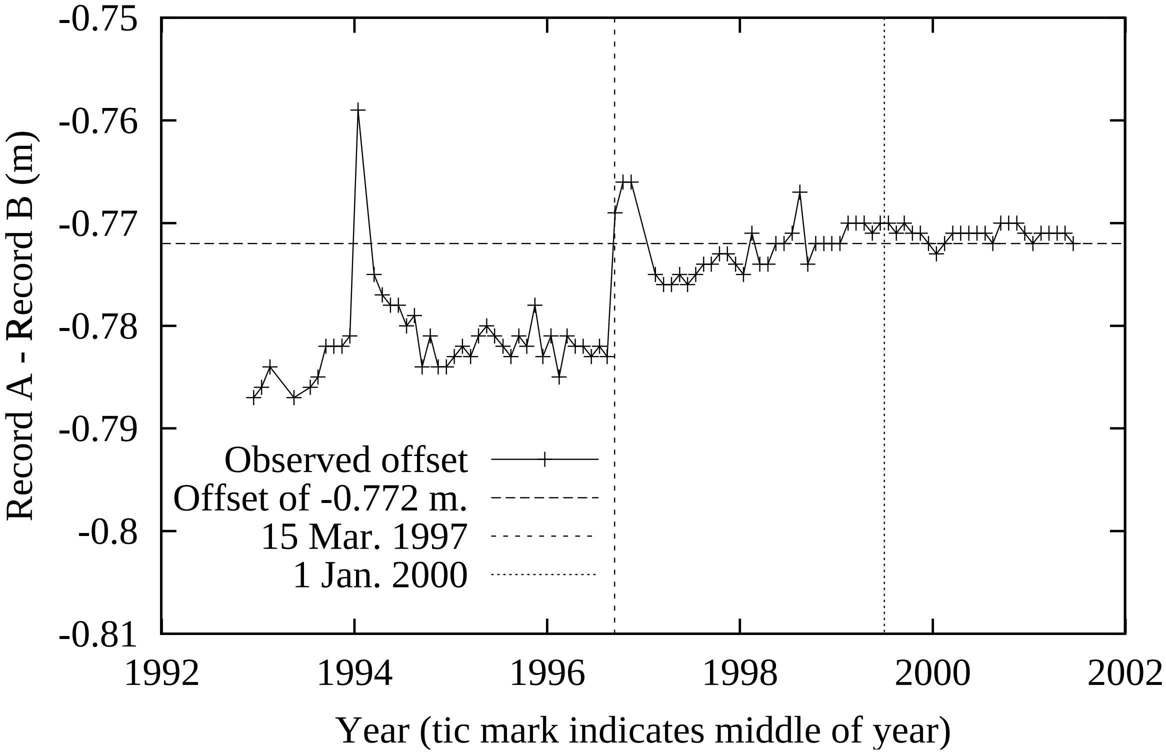

Figure 7: The difference between Records A_m and B_m.

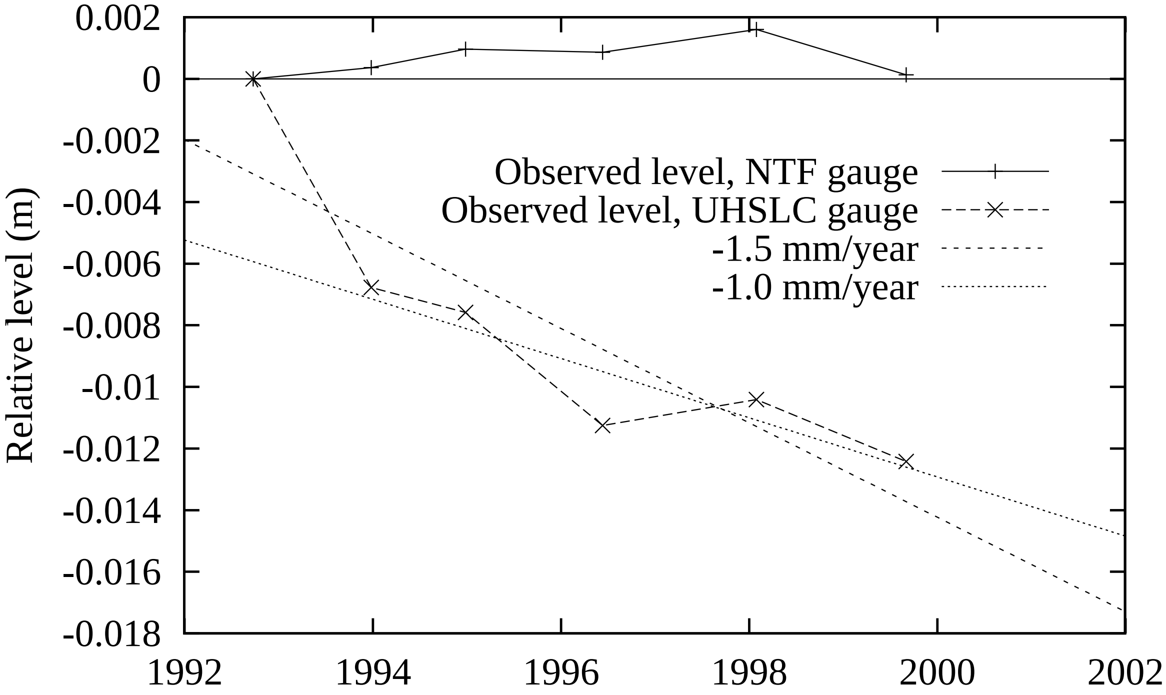

Figure 8: Results of levelling surveys of tide gauges.

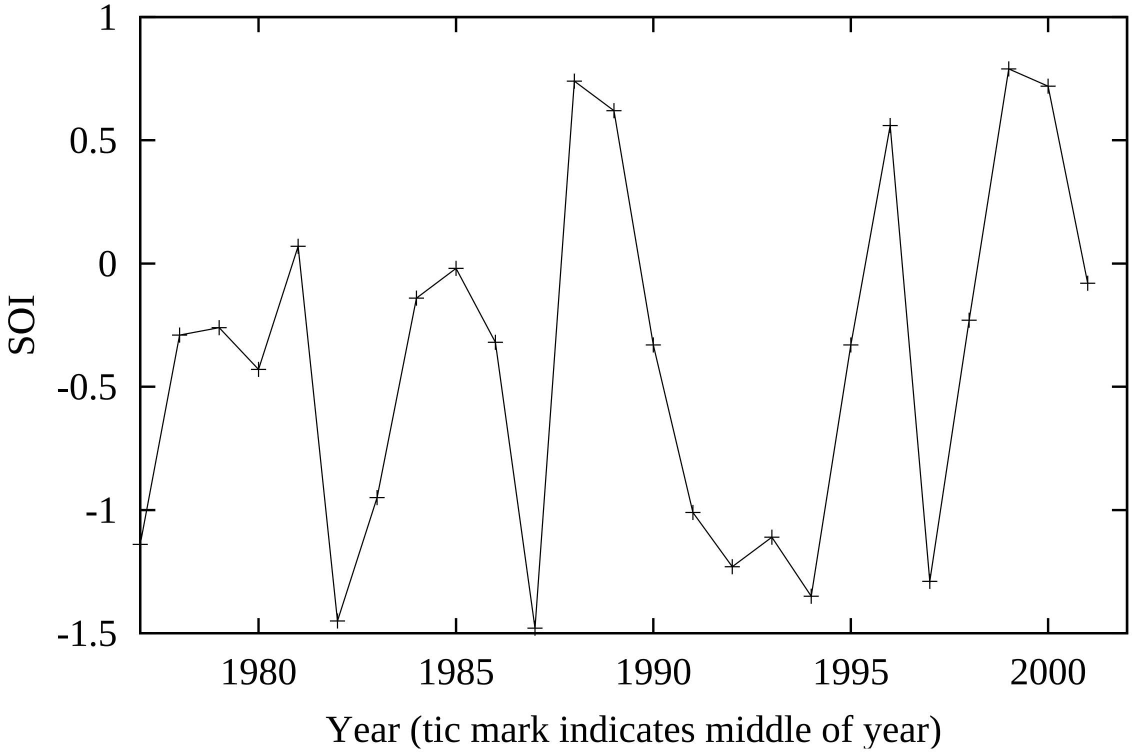

Figure 9: Annual values of the Southern Oscillation Index (SOI).

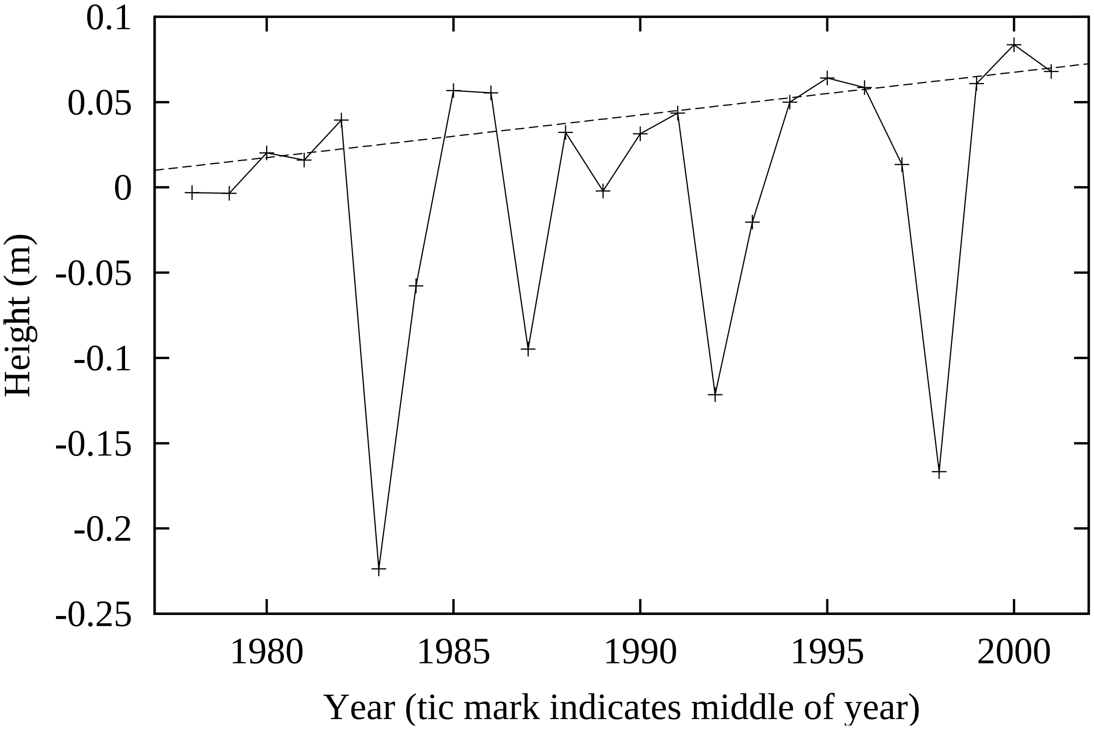

Figure 10: Results of Analysis I showing annual sea level data from UHSLC (Record A), with the time-averaged level removed, and superimposed approximate linear fit to non-ENSO points with a slope of 2.5 mm/year.

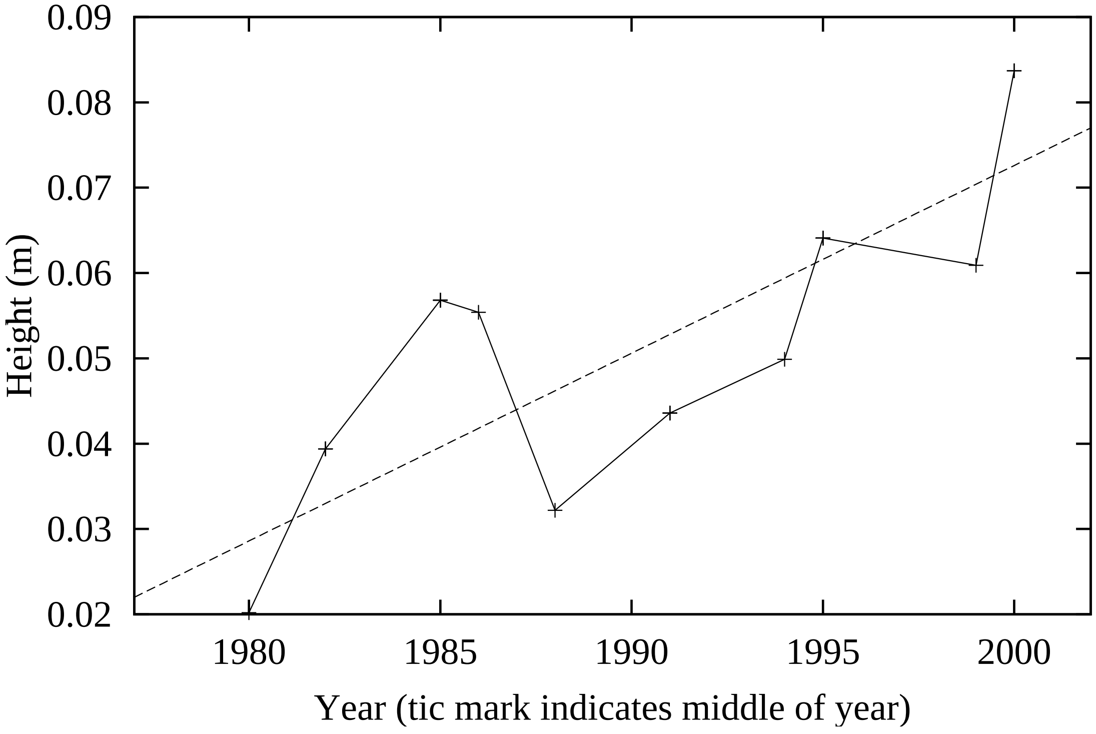

Figure 11: Results of Analysis I after the application of a four-year maximum filter, and superimposed approximate linear fit with a slope of 2.2 mm/year.

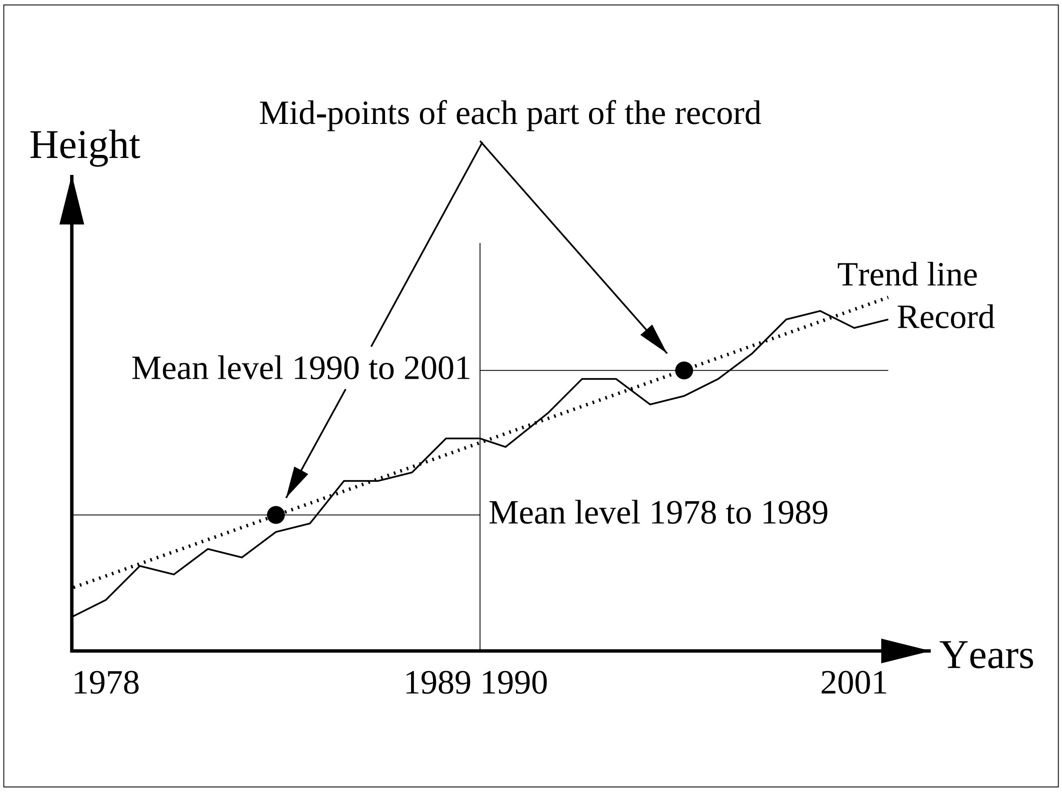

Figure 12: Schematic showing method of applying Analysis II to Record A.

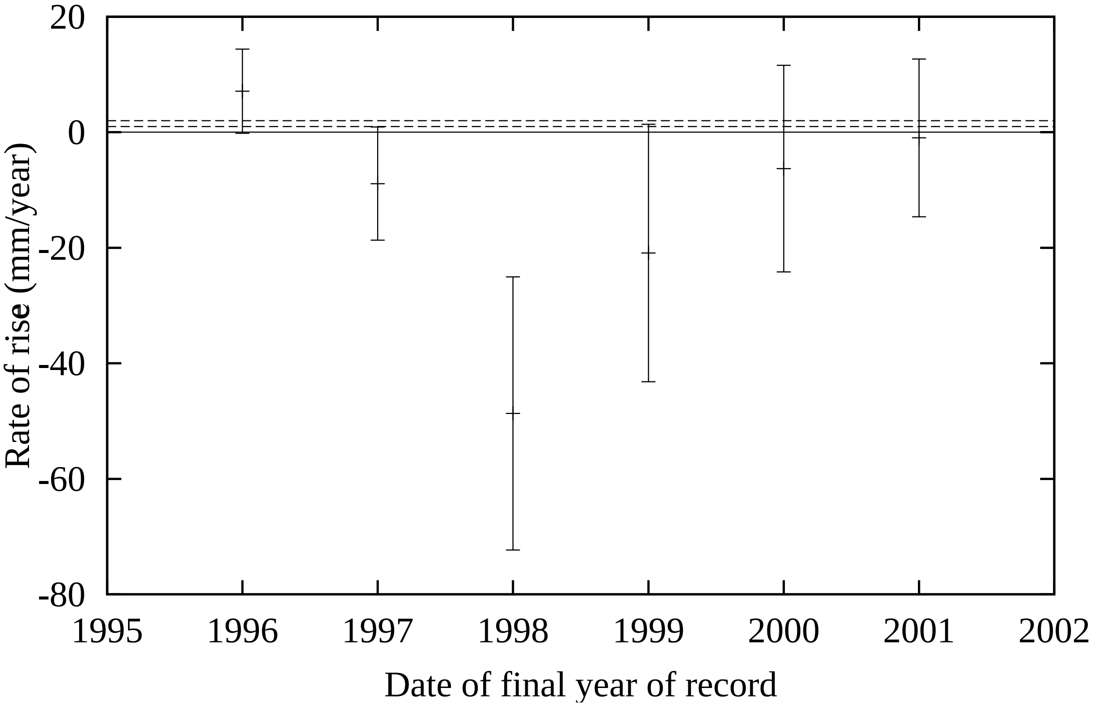

Figure 13: Results of Analysis III of Record B, terminated at the year shown. The horizontal dotted lines indicate the range of global average sea level rise during the 20th century, estimated by the IPCC (Church *et al.*, 2001).

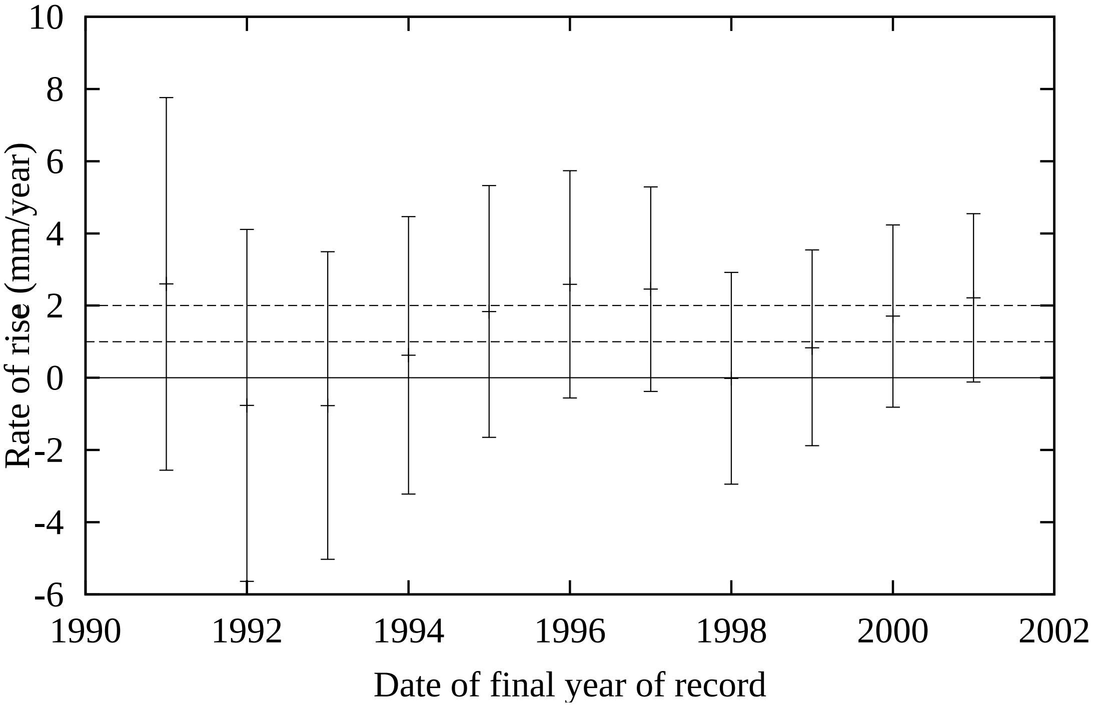

Figure 14: Results of Analysis III of Record A, terminated at the year shown. The horizontal dotted lines indicate the range of global average sea level rise during the 20th century, estimated by the IPCC (Church *et al.*, 2001).

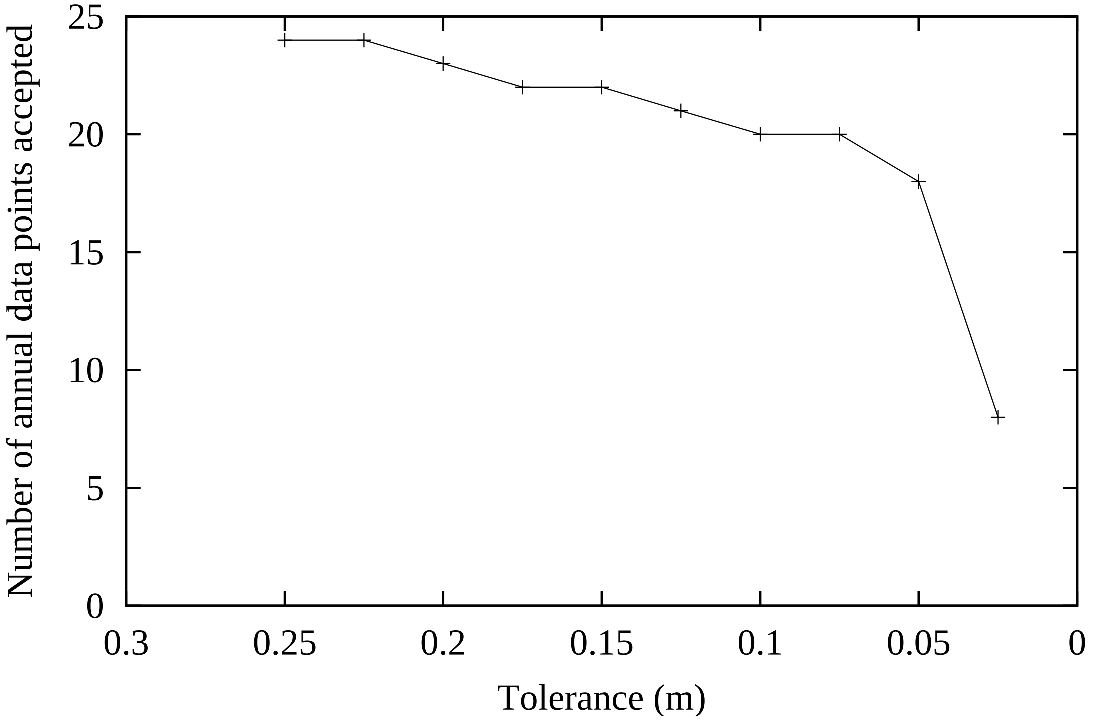

Figure 15: Results of Analysis IV of Record A, showing number of annual data points accepted based on the prescribed tolerance.

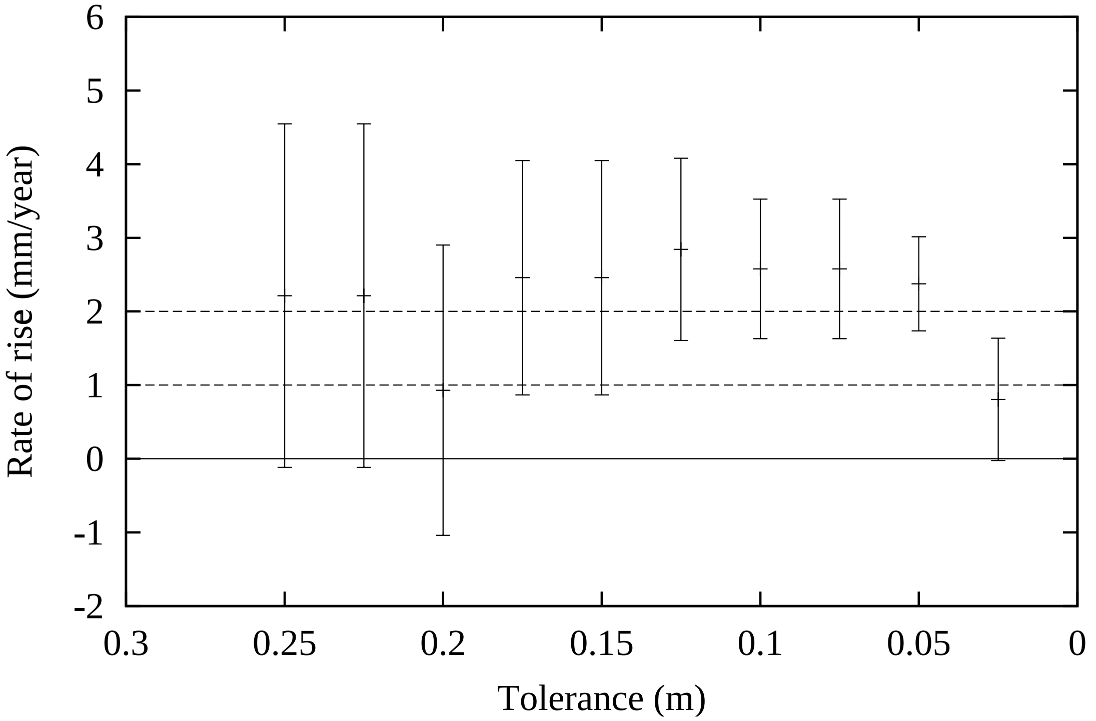

Figure 16: Results of Analysis IV of Record A, showing estimated trend and associated uncertainty based on the prescribed tolerance. The horizontal dotted lines indicate the range of global average sea level rise during the 20th century, estimated by the IPCC (Church *et al.*, 2001).

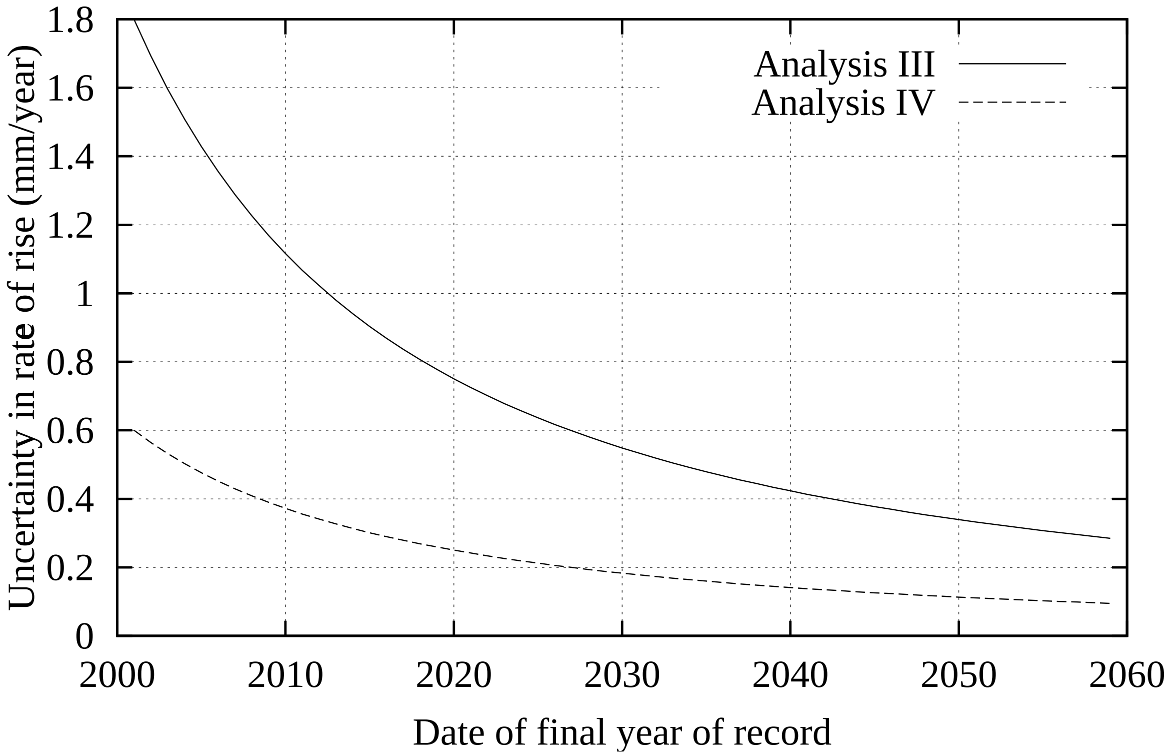

Figure 17: Uncertainties in estimated sea level rise for a range of record lengths from Funafuti.