

Linear and nonlinear sea-level changes at Durban, South Africa

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The tide record between 1970 and 2003 for Durban, South Africa, is analysed to determine the extent of recent linear and nonlinear sea-level trends in the light of predicted global sea-level rise. Given the stability of the adjacent land mass, Durban is ideally suited to test global sea-level change. The linear trends of monthly mean sea level revealed a sea-level rise of 2.7 ± 0.05 mm/yr and the yearly mean sea-level trend revealed a rise of 2.4 ± 0.29 mm/yr. Nonlinear trends varied between -1 mm and $+8$ mm/yr. These findings are similar to recently published results of global sea-level rise calculations over the last ten years derived from worldwide tide gauge and TOPEX/Poseidon altimeter measurements, which range between 2.4 and 3.2 mm/yr.

The need to determine trends in sea-level change

There is growing worldwide awareness of the effects of climate change induced by human actions on our planet and, particularly, of the global effect of sea-level rise on coastal cities, towns and subsistence communities that rely on the sea for income and food. Urban settlements have expanded rapidly over the last thirty years, especially in developing countries, making more people vulnerable to this risk.¹

Sandy beaches, which make up 34% of the world's coastline,² form an integral part of most coastal cities' tourism potential. Tourism is an important economic activity in KwaZulu-Natal, and Durban's beaches constitute the province's most important tourist attraction, with 73% of domestic tourists visiting them.³ Rising sea levels will reduce the surface area of beaches, and the consequent damage to tourism infrastructure will impact adversely on the local tourism industry.

Coastal harbours are similarly vulnerable. Durban plans to double its container port capacity over the next few years.⁴ Port and harbour development is costly and developers plan for use of this infrastructure for up to a century or more.

Measurement of sea-level change has been in progress for decades, with the main focus on the northern hemisphere. Data from tide gauges have traditionally been used for this purpose. In the late 1990s, however, the use of satellite data became more prominent, chiefly because of poor geographical coverage by tide gauges, the influence of tide gauge records by land movement and the superior accuracy provided by satellite data. Historically, the analysis of sea-level trends has been undertaken using linear regression techniques, but more recently nonlinear analysis has been introduced.⁵

This paper examines current rates of sea-level rise for Durban and surrounding coastal areas based on the tidal records of the South African Navy's tide gauge located near the harbour entrance ($31^{\circ}00'E$, $29^{\circ}49'S$) (Fig. A in supplementary material online). No such analysis has been done to date for Durban nor for any major coastal city on the east coast of Africa. The results are compared with published global sea-level changes.

Methods and results

The tide data used for this analysis were sourced from the South African Navy's Hydrographic Office. The most reliable records between 1970 and 2003 were selected and were received as hourly observed tide levels in Chart Datum (CD). The navy data were found to be unusable in their existing form. There are two other data records for Durban, one held by the British Oceanographic Data Centre (BODC) and the other by the Permanent Service for Mean Sea-level. These were evaluated and found also to contain several anomalies despite originating from a single tide recorder. This required a re-analysis of these data, to rectify and remove dubious records.⁶

The barometric data used in this study were obtained from the South African Weather Service, received as hourly recordings from the Durban International Airport weather station. Recorded tide data are influenced by meteorological effects. Compensation requires the extraction of the influence of barometric pressure, commonly referred to as 'inverted barometer' effects,⁷ as these can mask the true sea-level change. Correlation coefficients were established between changes in apparent sea levels, using the Durban tide gauge and changes in barometric pressure. These were -8.7 mm per hPa for annual readings and -5.9 mm per hPa for monthly readings (Mather, manuscript in preparation) and were applied to the data. The longer the period of analysis, the closer the correlation tended to the theoretical relationship of -9.9 mm per hPa.

Two different levels of analysis were undertaken. In the first method, using annual records, the data were analysed according to Pugh.⁸ This entailed refining the data, applying a weighting factor to account for discarded data, introducing a barometric correction and, finally, applying linear regression to the refined, weighted annual change. The second method used was similar to the first except for the omission of weighting factors, using monthly rather than annual change and the application of a barometric compensation of -5.7 mm per hPa, rather than the -8.7 mm per hPa used in the first method. Nonlinear trends for monthly mean sea levels were calculated using CATMV, a computer program developed by the Gistat group (www.gistatgroup.com), based on the singular spectrum analysis (SSA) method.^{9,10}

Results

The linear analysis of monthly mean sea levels (MMSL) yielded a rate of sea-level rise of 2.7 ± 0.05 mm/yr at the 95% confidence level (Fig. 1). The linear analysis of yearly mean sea level (YMSL) yielded a sea-level rise of 2.4 ± 0.29 mm/yr (Fig. 2). Nonlinear trends (Fig. 3) show changes similar to the linear trends. On examination of the moving annual average trends (Fig. 4), however, it is possible to distinguish different phases. These range from approximately -1 mm/yr to $+8$ mm/yr. Only two periods show a negative trend, these being in 1972 and 1992. The two negative trends are of small magnitude, -1.1 mm/yr and -0.6 mm/yr, respectively. A positive trend is evident in the rest of the series, with the highest value of $+8.4$ mm/yr recorded in 2002.

Discussion

Sea-level trends around the world have shown varying amounts of sea-level variation, depending on the location and geological history of the site. Emery and Aubrey¹¹ evaluated 587 gauges with records longer than ten years and identified only 36 that originate from stable coastlines. Only three of these sites were from southern Africa and all were situated on the west coast. As the southern part of the African continent is founded

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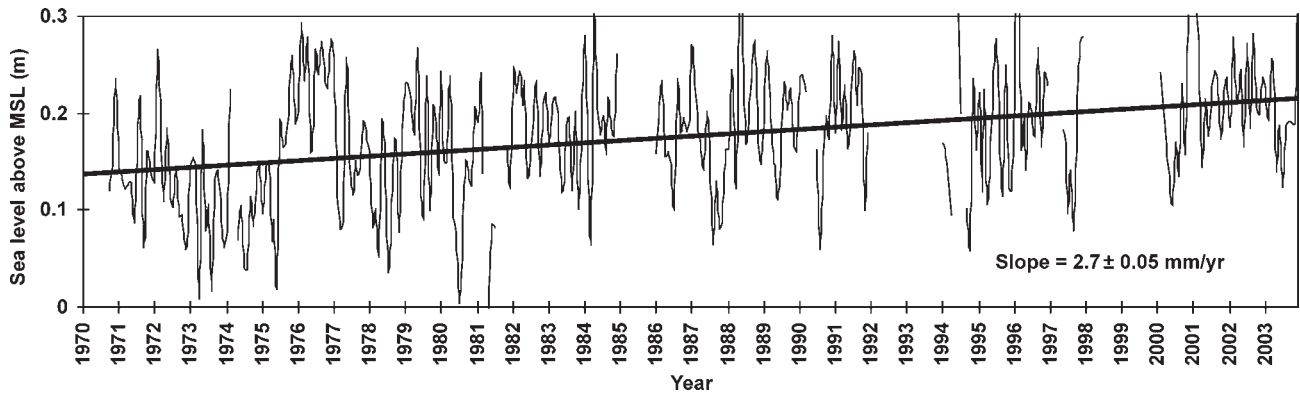


Fig. 1. Monthly sea-level changes at Durban and derived linear trend.

on a stable cratonic base, this makes the land mass around Durban tectonically stable.¹² This obviates the need to correct for many of the other influences that pervade the tidal records, notably subsidence and post-glacial rebound. Durban is, therefore, one of relatively few sites in the world that can be used directly to assess global sea-level change.

Little recent research has been conducted in South Africa on rates of sea-level change calculated from tide gauge data. In 1984, Brundrit¹³ focused on sea-level changes only on the west coast of South Africa, and Hughes *et al.*¹⁴ examined changes on the west and Cape coasts with respect to sea-level measurements in the global context of sea level. Brundrit¹⁵ examined the tide gauge data at Lüderitz, Port Nolloth, Simon's Town and Mossel Bay, deriving trends from these sites. He omitted the east coast entirely, however. Except for the work of Cooper^{12,16,17} and Hughes,¹⁸ who used estimates of sea-level change to model coastal impacts, even fewer sea-level studies have been undertaken specifically for Durban.

A comparison of our results with this previous work was made. Cooper,¹⁶ quoting Hughes (pers. comm.), refers to Durban's tide record as showing 'little upward trend' and ascribes this to possible instrument error, land movement and/or other factors. This paper examines this particular period of the Durban record, and analysis clearly shows an upward trend. This anomaly may be attributable to previous workers' use of the British Oceanographic Data Centre record for Durban, which shows a downward trend, and not the official tide record from the South African Navy. The BODC record originates from the University of Cape Town via the University of Hawaii. The work of Cooper^{12,16} included a regional estimation of the effects that a 1-m sea-level rise could have on the KwaZulu-Natal coastline. This figure was chosen presumably as it reflected the upper limit of sea-level rise predictions at that time. All other previous work has been based on scenarios and none of the authors derived the

actual sea-level rise for the east coast from tide data. Thus the data from this study are vital for future work.

The approach adopted in this study, based on MMSL and YMSL data from the available records, provides good correlation with more sophisticated analyses. Pugh⁸ points out that: 'This method is used by many authorities because it requires little mathematical insight, yet produces values close to that obtained by more elaborate tide-elimination techniques (Rossiter, 1958).'

It is important to note that calculations based on mean monthly sea level almost always yield different answers to those based on yearly mean sea-level calculations. Time series plots of YMSL values appear to be smoother than those of MMSL values. As there are 12 times more data points in the mmSL record, however, this effectively increases the sample size of MMSL plots, leading to a smaller standard error of the regression coefficient.

Linear regression analysis is a relatively easy and popular tool whereby sea-level trends can be obtained. This method has its defects, however. Regression analysis is sensitive to the starting position of the analysis and, therefore, is inappropriate for periods of a decade or less, because of the multi-year cycles present in the tide record.^{5,19} These cycles, if not properly accounted for in the analysis, mask longer-term trends in the data.

Nonlinear techniques, on the other hand, are more robust and not as sensitive to the start position. Two approaches considered for this analysis were the empirical mode distribution (EMD)^{20,21} and singular spectral analysis (SSA).⁹ Both are effective in decomposing time series into trends and residual frequencies, allowing better understanding of the latent trends in the data. As with most data series, however, gaps are common and are difficult to deal with. CATMV, which uses SSA, was chosen here, as this software has a superior method of filling in data gaps.¹⁰

The comparison of these results with worldwide figures is shown in Table 1. Over the last century, the trend is towards an

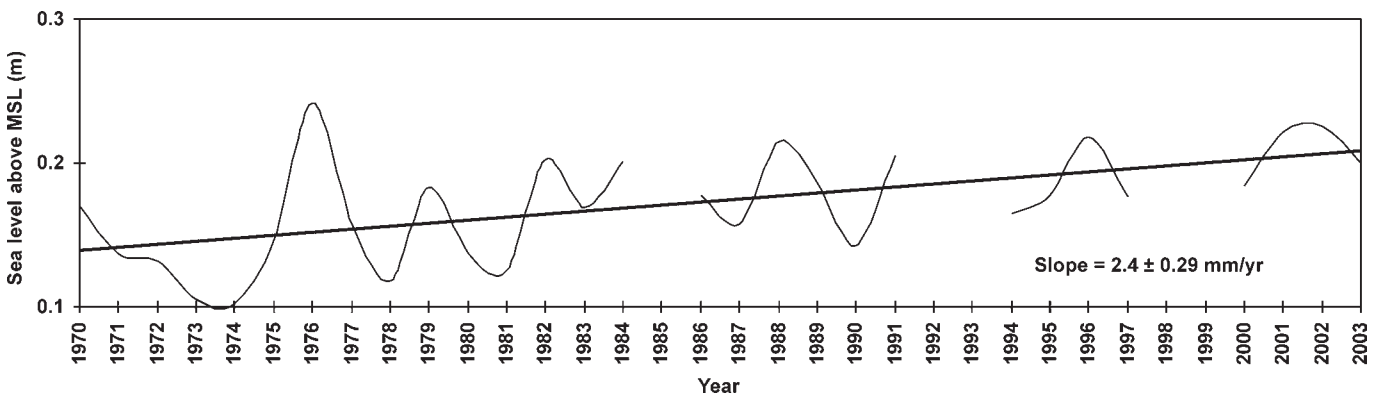


Fig. 2. Annual sea-level changes at Durban and derived linear trend.

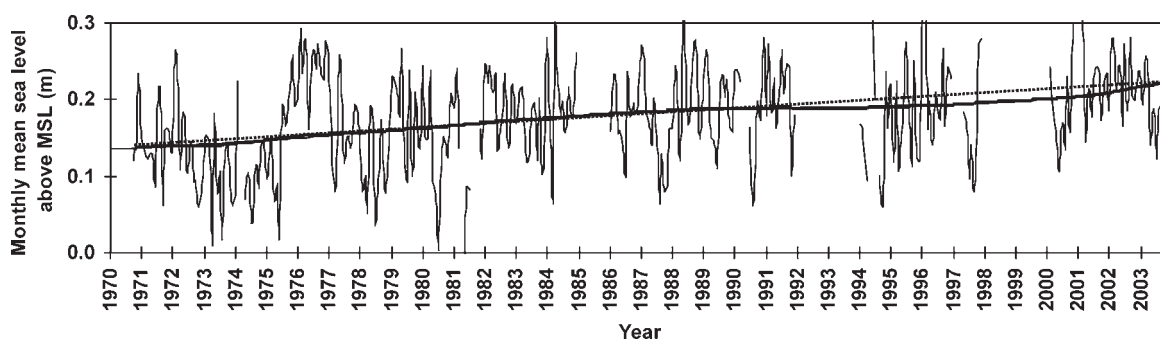


Fig. 3. Monthly sea-level changes at Durban and derived non-linear trend. The dotted line shows deviation from the linear trend.

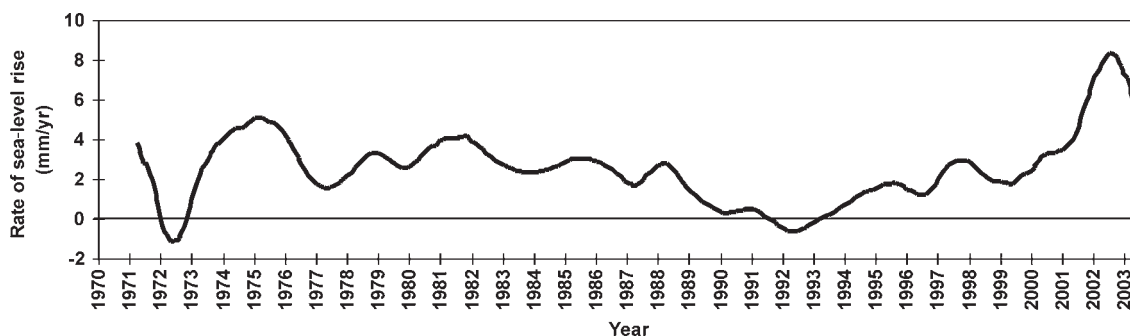


Fig. 4. Annual rate of sea-level change at Durban.

ever increasing rise-rate, which has led to speculation about future acceleration in rising sea levels. Church and White⁴³ have subsequently established evidence of an acceleration in the rate of sea-level rise from extended (1870–2004) tide gauge records. For this reason comparisons with other sea-level changes are confined to time periods relevant to this study. Church and White⁴³ examined the 1970–2003 period and obtained a global sea-level rise of 2.1 mm/yr. Many new analyses have been undertaken as a result of satellite altimeter data becoming available, Cabanes *et al.*³³ and Nerem and Mitchum³⁴ examined global sea-level rise for the period 1993–1998 and arrived at a figure of 3.2 ± 0.2 mm and 2.5 ± 1.3 mm/yr, respectively. Jevrejeva *et al.*⁵ derived a figure of 2.4 ± 1.0 mm/yr for the period 1993–2000. More studies were undertaken as the satellite data extended over longer time periods. Cazenave and Nerem⁴¹ and Leuliette *et al.*⁴² examined sea-level change over the period 1993 to 2003 and published results of approximately 2.8 ± 0.4 and 3.1 ± 0.7 mm/yr. Bindoff *et al.*⁴⁴ updated the work of Cazenave and Nerem⁴¹ and obtained a linear rate of sea-level rise of 3.0 mm/yr. All of these results are comparable and correlate well with the linear results of 2.7 ± 0.05 mm/yr obtained for Durban.

Nonlinear results show a constantly changing trend influenced by the multitude of different global changes at play. Analysis shows that, apart from one short period between 1972 and 1973, the major part of the record revealed an upward trend of varying degree. The period between 1972 and 1973 shows a downward trend of -2 mm/yr. The next period, which accounts for most of the time series, yields an almost uniform trend of $+2.6$ mm/yr.

A distinct advantage of nonlinear trends over linear trends is that discrete periods can be analysed against results obtained for comparable periods. A comparison for the period 1993–98 with the results obtained by Nerem and Michum³⁴ from satellite data of 2.5 ± 1.3 mm/yr indicates trends from this study of 1.9 mm/yr, which falls into the range provided by Nerem and Michum. Cazenave and Nerem⁴¹ and Leuliette *et al.*⁴² undertook a further study for the period 1993–2003, which yielded 2.8 ± 0.4 mm and

3.1 ± 0.7 mm/yr and, compared to the result of 3.0 mm/yr obtained in this study, showed excellent agreement with global nonlinear variations of sea levels.

Based on the comparisons above, the linear rate of sea-level rise derived for Durban of 2.7 ± 0.05 mm/yr would appear to be valid for use at Durban and the surrounding areas.

Table 1. Published information on global sea-level rise.

Reference	Year	Period of time considered	Average rate of sea-level rise \pm s.d. (mm/yr)
Peltier ²²	1996	1920–1970	1.94 ± 0.6
Davis & Mitrovica ²³	1996	Unspecified	1.5 ± 0.3
Douglas ²⁴	1997	1880–1996	1.9 ± 0.1
Nerem <i>et al.</i> ²⁵	1997	1993–1997	2.1 ± 1.2
Vilibic ²⁶	1997	1807–1992	1.5–2.0
Lambeck <i>et al.</i> ²⁷	1998	1892–1991	1.1 ± 0.2
Mitchum ²⁸	1998	1993–1996	2.3 ± 1.2
Cazenave <i>et al.</i> ²⁹	1998	1993–1997	1.4 ± 0.2
Woodworth ³⁰	1999	1900–1998	1.22 ± 0.25
Nerem ³¹	1999	1993–1998	2.5 ± 1.3
Peltier ³²	2001	20th century	1.84–1.91
Cabanes <i>et al.</i> ³³	2001	1993–1998	3.2 ± 0.2
Nerem & Mitchum ³⁴	2001	1993–1998	2.5 ± 1.3
Proshutinsky <i>et al.</i> ³⁵	2001	1950–1990	1.8
Church <i>et al.</i> ³⁶	2001	20th century	1.0–2.0
Lambeck ³⁷	2002	1914–2002 1897–1990	1.16 1.65
Johansson ³⁸	2002	1993–2000	1.9 ± 0.2
Hunter <i>et al.</i> ³⁹	2003	1841–2002	1.0 ± 0.3
Church <i>et al.</i> ⁴⁰	2004	1950–2000	1.8 ± 0.3
Cazenave & Nerem ⁴¹	2004	1993–2003	2.8 ± 0.4
Leuliette <i>et al.</i> ⁴²	2004	1993–2003	3.1 ± 0.7
Church & White ⁴³	2006	1870–2004 1900–2004 1970–2003	1.44 1.7 ± 0.3 2.1
Jevrejeva <i>et al.</i> ⁵	2006	1993–2000 1920–1945	2.4 ± 1.0 2.5 ± 1.0
Bindoff <i>et al.</i> ⁴⁴	2007	1993–2003	3.0

Conclusion

The rate of sea-level rise of 2.7 ± 0.05 mm/yr for Durban and its adjacent coastline is consistent with previous worldwide research, clustering in a band between 2.4–3.2 mm/yr. These results are important in that they provide for the first time a locally measured rate of sea-level rise that can be used for strategic coastal planning, coastal management, and in the design of future port infrastructure and marine structures in the region.

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Supplementary material to:

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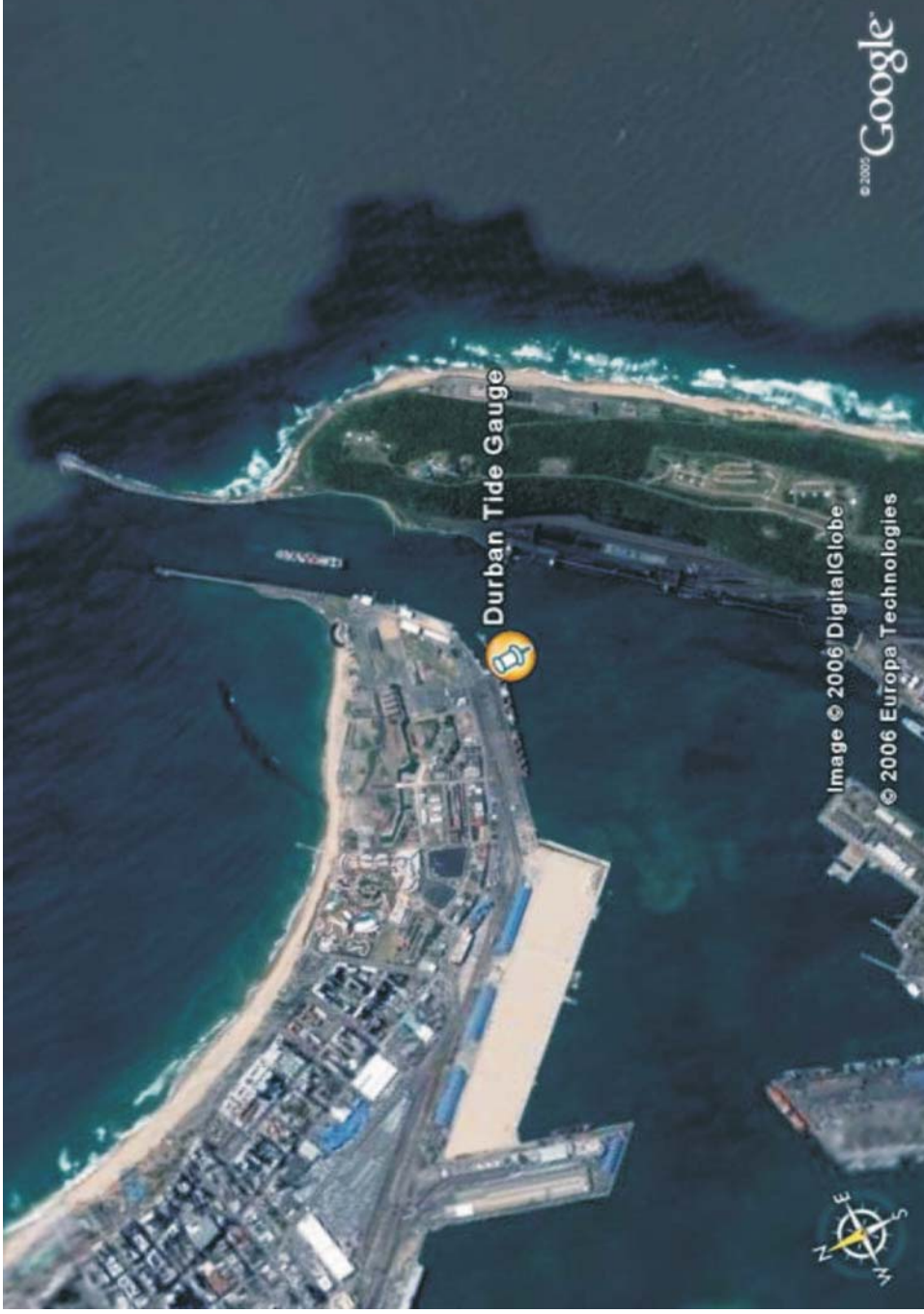


Fig. A. The location of the tide gauge in Durban harbour. [Source: eThekweni Municipality.]