African Journal of Marine Science 2009, 31(2): 145–156
Printed in South Africa — All rights reserved

AFRICAN JOURNAL OF
MARINE SCIENCE
ISSN 1814–232X EISSN 1814–2338
doi: 10.2989/AJMS.2009.31.2.3.875

Southern African sea levels: corrections, influences and trends

AA Mather[1]*, GG Garland[2,3] and DD Stretch[4]

[1] Coastal and Catchment Policy, Co-ordination and Management, Engineering Unit, eThekwini Municipality, PO Box 680, Durban 4000, South Africa
[2] Department of Geography and Urban Planning, University of the United Arab Emirates, Al Ain, UAE
[3] School of Environmental Sciences, University of KwaZulu-Natal, Durban 4041, South Africa
[4] School of Civil Engineering, University of KwaZulu-Natal, Durban 4041, South Africa
* Corresponding author, e-mail: mathera@durban.gov.za

Manuscript received October 2008; accepted May 2009

The tidal records of existing South African and Namibian tide gauges are examined and corrected. Regional sea level trends vary, with the West Coast rising by +1.87 mm y^{-1} (1959–2006), the southern coast by +1.48 mm y^{-1} (1957–2006) and the East Coast by +2.74 mm y^{-1} (1967–2006). The effects of barometric pressure and vertical crustal movement changes on these trends are examined. The derived relationship between sea levels and barometric pressure changes varied between 5.71 and 7.67 mm hPa^{-1}, significantly less than the theoretical inverse barometric correction. Barometric pressure has been dropping along the west coast at 1.63 hPa per decade (1987–2006), has remained fairly static along the southern coast and is rising at 0.30 hPa per decade (1970–2007) along the east coast of southern Africa. The West Coast barometrically corrected sea level trends show that most of the change can be attributed to falling barometric pressure, whereas along the East Coast, the barometric pressure increase is suppressing sea level by 0.2 mm y^{-1}. Vertical crust movements vary, with the largest recorded movements of +1.11 ± 0.25 mm y^{-1} found along the East Coast. Movement rate reduces southwards. Eustatic sea level trends vary from +3.55 mm y^{-1} along the East Coast and +1.57 mm y^{-1} along the southern coast to +0.42 mm y^{-1} along the West Coast.

Keywords: barometric pressure, sea level rise, tide levels

Introduction

Sea levels vary in time and space because of a variety of natural factors acting on the Earth's surface (Church et al. 2001, Bindoff et al. 2007), including solar and lunar tides (Pugh 2004), waves and winds (Pugh 1987), crustal movements (Baker 1993, Pirazzoli et al. 1994, Davis and Mitrovica 1996) and atmospheric conditions (Dickman 1988, Hoar and Wilson 1994, Wunsch and Stammer 1997, Proshutinsky et al. 2004), at both a localised and regional scale. The anthropogenic effects on the planet have altered this natural state of dynamic equilibrium. These influences include warming (Warrick et al. 1996, Bindoff and McDougall 2000), glacier and ice sheet melt (Dyurgerov and Meier 1997) and surface and ground water storage (Gornitz 2000).

Over the past several decades, driven by the concerns about the impacts of global warming, many researchers and organisations, such as the Intergovernmental Panel on Climate Change (IPCC), have sought to understand man's influence on global sea levels (IPCC 1990, 1996, 2001, Bindoff et al. 2007). Part of this research has been focused on the current and future rate of sea level rise (Church et al. 2001). Until the introduction of satellite altimetry in 1993 (Nerem et al. 1997), the analysis of sea level changes had been solely confined to tide gauge data, which was predominately based in the Northern Hemisphere. The use of satellite sea level data has to some extent improved the geographical coverage; however, accurate tide gauge data are still needed to calibrate the satellite altimeter results (Mitchum 1998).

Unfortunately, in the Southern Hemisphere, not many tide gauge records extend for longer than 50 years, the period deemed to be suitable for this type of analysis (Woodworth 1990, Douglas 1991). In the African context, the number of suitable tide gauge records diminishes even further, but there are plans to extend and upgrade this network along the African coastline (Woodworth et al. 2007).

This paper focuses on the tide gauges along the southern African coastline (Figure 1). Whereas, not all the records meet the 50-year length criteria, it is important that some preliminary analysis be undertaken to help in making key planning and policy decisions. Investigations on sea level changes around the South African coastline are limited. Earlier work focused on sea level changes on the West Coast (Brundrit 1984) and on the West and Cape coasts (Hughes et al. 1991). Later, Brundrit (1995) derived sea level trends from tide gauge data taken from Lüderitz in Namibia and Port Nolloth, Cape Town and Mossel Bay on the West and South coasts. Recently, Mather (2007) examined the linear and non-linear sea level trends for Durban on the East Coast.

Key to understanding these trends in sea level changes in a global context is the ability to separate out the various contributions by tides, waves and winds, which can be simply measured using tide gauge data, over as long a period as possible. However, other important factors that can influence sea level such as vertical crustal movements and barometric pressure are more difficult to quantify. These parameters are briefly outlined below.

Vertical crustal movements

Although South Africa is located on a stable cratonic base (Cooper 1995, Ramsay and Cooper 2002), the African plate is subject to motion induced by the plate and rebound movement on account of historical glacial ice sheet loading. Vertical crustal movements have been difficult to quantify in the past because they have mainly been estimated using various models, e.g. the ICE-5G model (Peltier 1994). With the advent of satellites, it has become possible to measure the land and water surface of the earth against an imaginary geoid to determine the vertical and horizontal changes in the Earth's crust. This network of monitoring points is relatively sparse over southern Africa, with only two stations in South Africa located at the coast at Simon's Town and Richards Bay (Figure 1). These geodetic stations are located next to tide recording stations. Despite data limitations, corrections for vertical land movements are applied here to the observed sea level changes in order to provide some indication of eustatic sea level rise around the southern tip of Africa.

Barometric pressure

Barometric pressure has been reported to be the second-most important climatic variable other than temperature that may be influenced anthropogenically (Gillett et al. 2003). Global barometric pressure trends yield a small positive trend of +0.02 hPa y^{-1}, with values of –0.03 hPa y^{-1} occurring in localised areas (Church et al. 2001). Northern European trends are of the order of +0.01 hPa y^{-1} (Woodworth 1987). Trends for short periods (1960–1990) can have a larger influence on sea level trends of between –0.05 mm y^{-1} (Schönwiese et al. 1994) and +0.04 mm y^{-1} (Schönwiese and Rapp 1997). Thus, it is important that the impacts of local barometric pressure variations are understood and properly taken into account in the assessment of trends using tidal records over a relatively short time

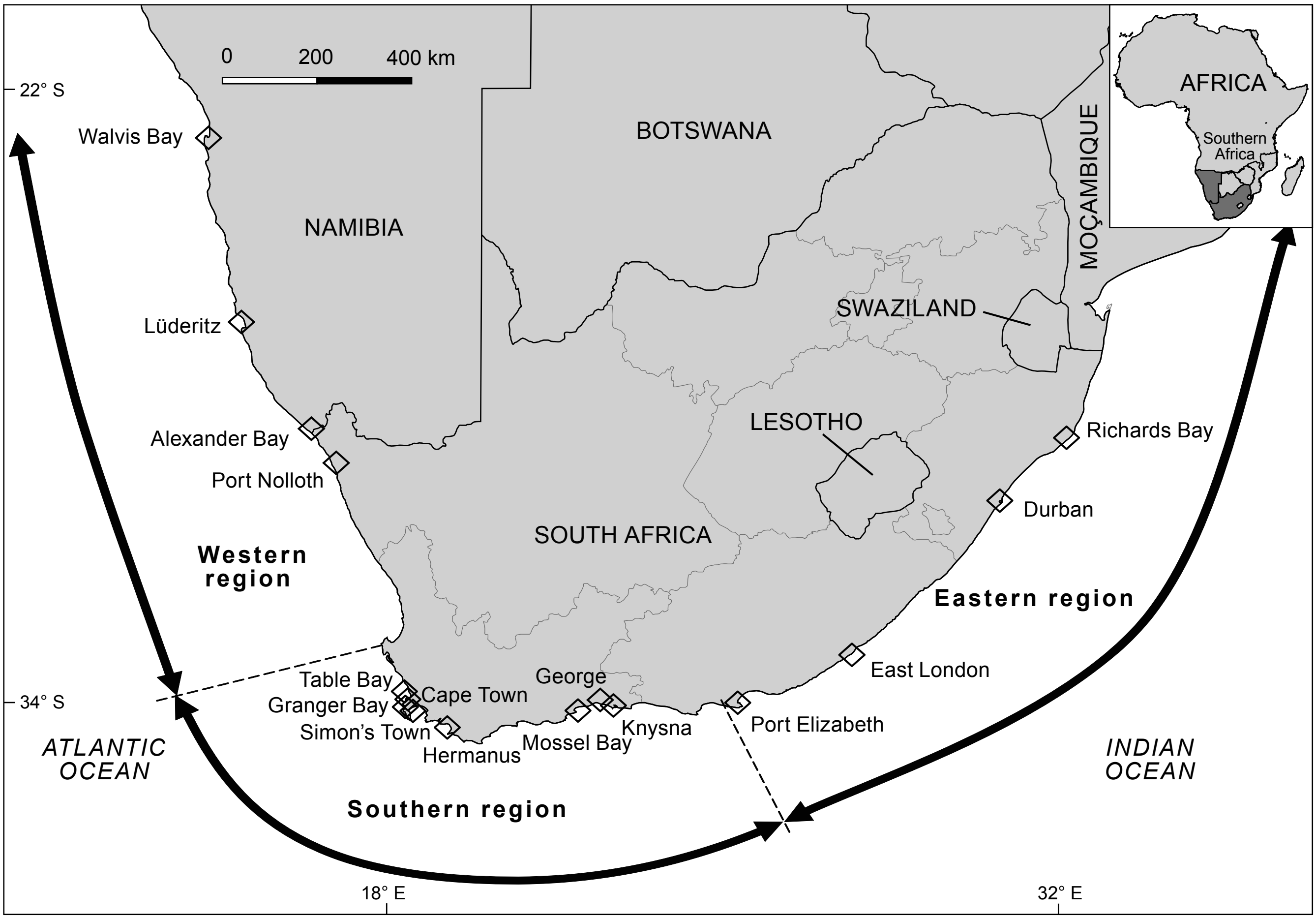

Figure 1: Map of southern Africa showing the location of the tide gauge stations and the three geographical regions referred to in the text

period. In southern Africa, where the available records of sea level are only up to 37 years long, it is critical to ensure that barometric pressure effects are taken into account in the calculation of eustatic sea level change.

The barometric pressure relationship is governed by the simple relationship that increased air pressure forces the sea surface to drop and the excess water is distributed to other regions of the sea. This relationship has been widely studied and was first postulated by Gissler (1747; cited in Roden and Rossby 1999). Doodson (1924) continued this work and coined the term ‘inverted barometer response’, which is now in common use (Rossiter 1962, Roden 1966, Wunsch and Stammer 1997). From the hydrostatic equation, it can be deduced that a barometric high or low pressure system should theoretically depress or elevate the sea surface. The theoretical ‘local inverted barometer’ (IB) correction for the sea surface can be calculated as:

$$\zeta_{IB} = -0.9948 \times (p_a - 1013.3)$$

where ζ_{IB} is the change in sea level in cm, p_a is the recorded barometric pressure in hPa, 1013.3 is the standard atmospheric pressure at sea level in hPa and –0.9948 is the IB coefficient in cm hPa^{-1} (Hoar and Wilson 1994).

The equation shows that each hPa drop in pressure leads to a 9.948 mm (often approximated to 10 mm) increase in sea level. The exact inverted barometer response is seldom found in practice (Pugh 1987) and tide gauges around the world will have different responses to this relationship, depending on many factors including the amount of storm surge influenced by wind, as well as basin characteristics, continental shelf configurations, water depth, coriolis effect, ocean upwelling, and global and local atmospheric pressure realignments. The variation of barometric pressure over the sea can have a significant influence on recorded tide levels, which at times can be of orders of magnitude greater than the annual change in sea levels (Bell et al. 2000, Singh and Aung 2005). Working on global data, Ponte (2006) found that the deduction of the IB signal can have the effect of up

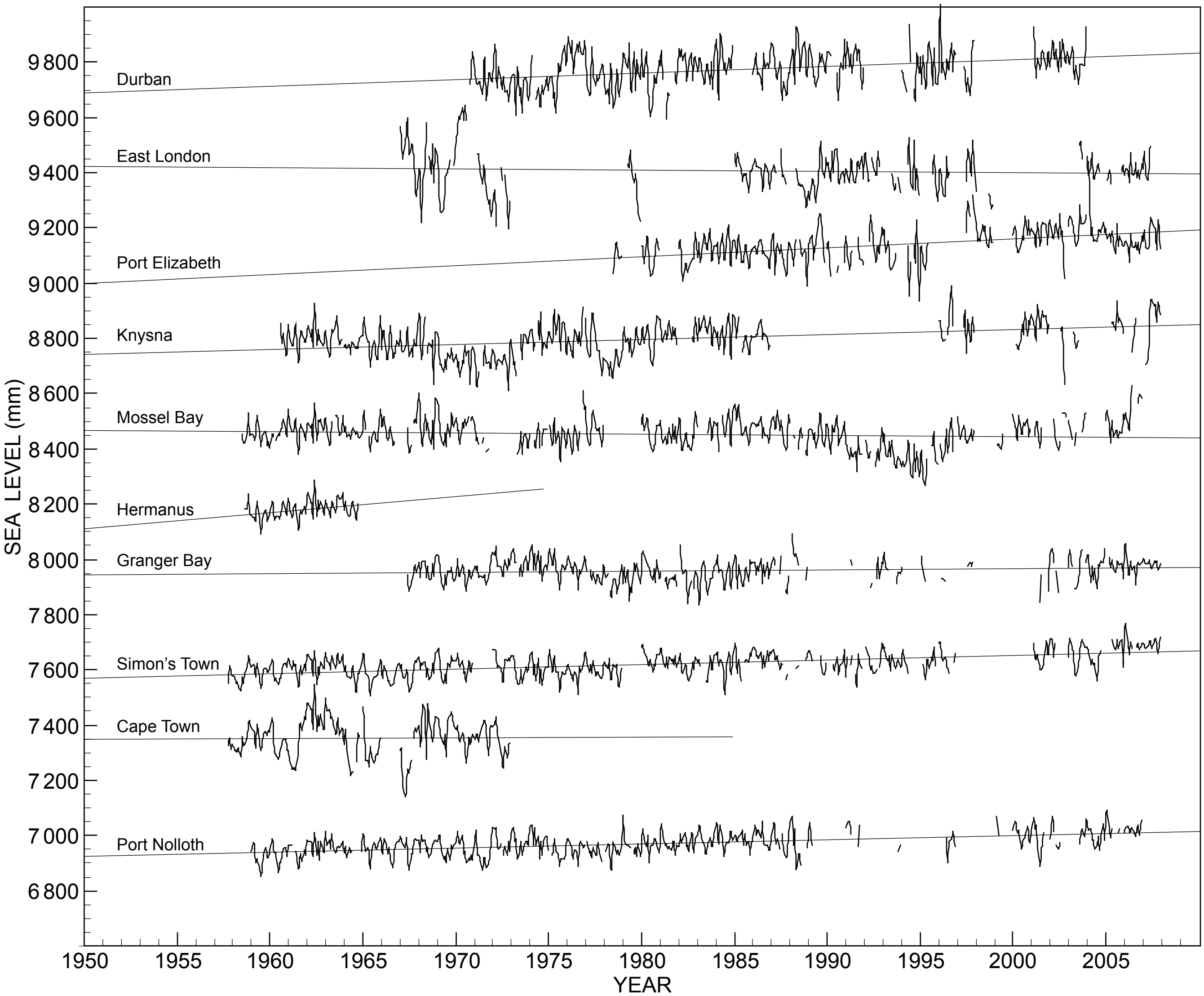

Figure 2: Tide gauge time-series for the different stations, 1959–2006

to a 40% change in the sea level trend. The understanding of this relationship is critical in isolating the weather effects from short tidal records if sea level changes are to be accurately computed.

The objectives of this paper are to determine (1) the current relative rate of sea level rise at stations around the southern African coastline, (2) the regional relative rates of sea level rise, (3) the impact of changes in barometric pressure on sea levels, (4) the influence of vertical land movements on sea levels, and (5) the regional rate of eustatic sea level rise along the coastline.

Material and methods

The analysis of the sea levels and their respective influences was based on a number of datasets. In some cases, more than one dataset was available and a choice was made between them, for the reasons given below. The monthly and annual revised local reference (RLR) tidal dataset for all South African and Namibian tide gauge stations was sourced from the Permanent Service for Mean Sea Level (PSMSL) at www.pol.ac.uk/psmsl. The tide data for Durban were derived from Mather (2007, 2008), which required rectifying some errors (detailed below). The sea level data used in this study are shown in Figure 2.

Sea level pressure data (HadSLP2) were sourced from the Hadley Centre for Climate Change, UK, and monthly barometric pressure data were obtained from the South African Weather Service. The HadSLP2 data are in 5° × 5° grids for the period 1955–2004. Examination of the area of interest in this study revealed that in half of the grids required for the analysis, only one land station was located in the grid. Because the tide gauge and weather station pairs to be examined (Alexander Bay and Port Nolloth) were not further than 80 km apart, the actual weather station data rather than the HadSLP2 data were used (Figure 3).

Vertical crustal movement data were available as model outputs at all the tide station sites from both the ICE-5G (VM2) and (VM4) models and were obtained from the PSMSL website. Vertical crustal movement from GPS stations coupled with tide gauge stations were supplied by the Hartebeesthoek Radio Astronomy Observatory, South Africa (HartRAO).

A simple linear regression analysis was used to determine annual sea level trends from the monthly and annual tide gauge data. For each location, a proxy IB coefficient was determined from the correlation of recorded monthly sea levels and barometric pressure. A linear regression analysis was undertaken on a scatterplot to determine the slope of the line and hence the proxy IB coefficient applicable to monthly records of sea level. From these results, two methods were used to determine the effect of barometric pressure changes on the sea level trends. Method 1 involved the direct arithmetic deduction of the barometric trends from the sea level trends at each of the locations. Method 2 involved correcting the monthly sea level for

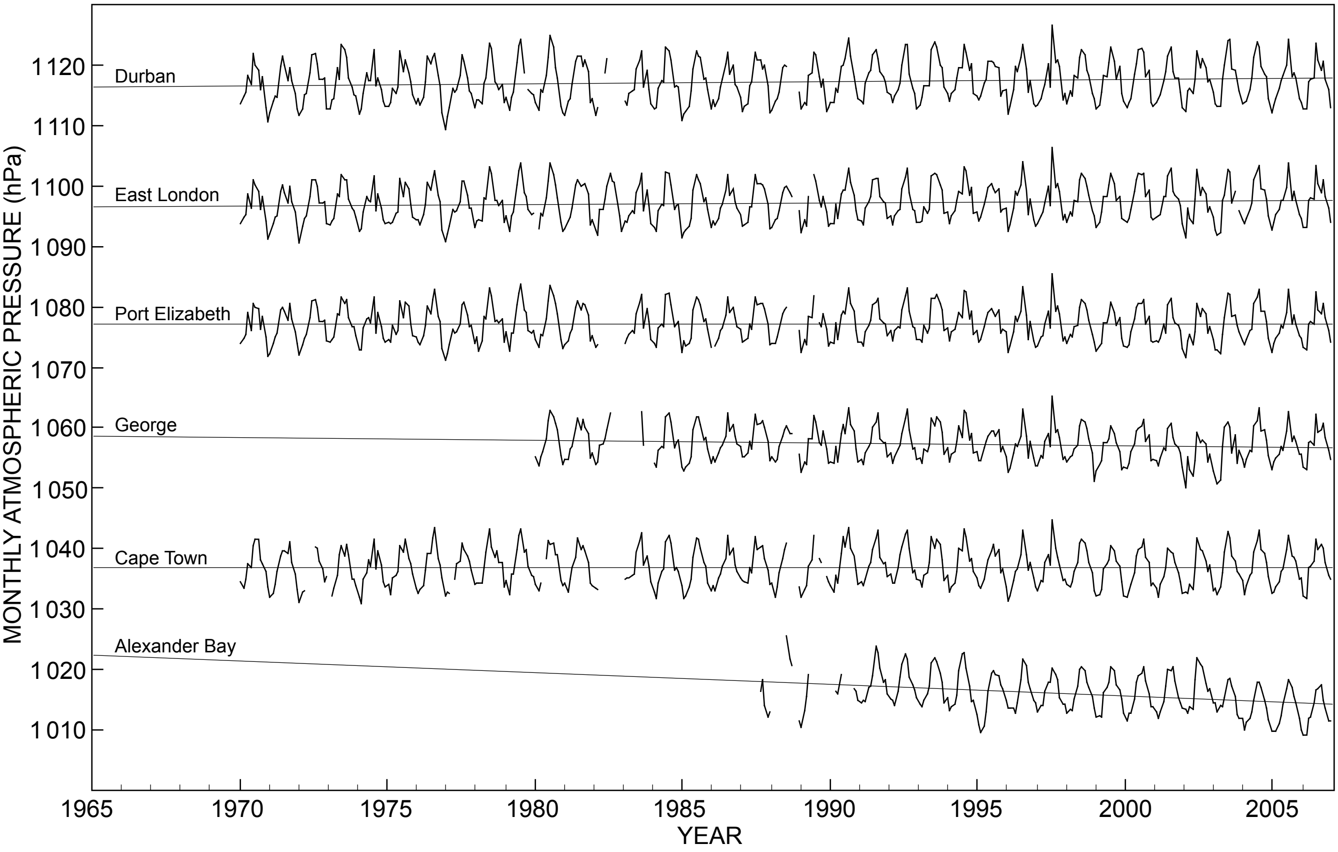

Figure 3: Monthly barometric pressure recordings for the different stations, 1970–2007

every monthly recording at each of the locations, and thus a trend of the barometrically corrected sea levels could be calculated for each station. Both methods utilised the derived proxy IB coefficient for each station (e.g. Durban's proxy IB coefficient used was –6.04 mm hPa^{-1}). This process was repeated for annual tide gauge data, but owing to the small series of annual data, the analysis was confined to Method 1 only.

Results and discussion

The main problem with the South African tide gauge records is confined mainly to the period between 1998 and 2002 when the data for recorded tide levels were confused with the mean level (ML) at each site. In the derivation of the chart datum (CD) to land levelling datum (LLD) conversion, an error was inadvertently introduced. This error was first identified during the analysis of the Durban sea level records (Garland and Mather 2007) and has subsequently been found in other South African tide gauge records. The magnitude of the error varies between sites (Table 1). This over-correction resulted in artificially raising sea levels for the period 1998–2002 (Garland and Mather 2007). To obtain the correct LLD sea levels for the tide gauge locations, it was necessary to correct all records. This was achieved using Table 2, which is based on the South African Navy's conversion table (SAN 2008). Due to these problems, we used the PSMSL revised local reference (RLR) data, excluding Durban, where additional data-correction processes have been applied. It should be noted that data for the period 1998–2002 have been largely removed from the RLR data by the PSMSL, possibly for the abovementioned reasons.

Sea levels from the various southern African locations using the PSMSL RLR data (excluding Durban) exhibited a scatter between rising and falling sea level (Figure 2). At each tide gauge location, an analysis of relative sea level trends was undertaken (Table 3). All stations showed a rising sea level, except for Mossel Bay where there was a change of –0.40 ± 0.19 mm y^{-1}. Low results from Walvis Bay (+0.38 ± 0.33 mm y^{-1}), Granger Bay (+0.08 ± 0.20 mm y^{-1}) and East London (+0.17 ± 0.05 mm y^{-1}) appear to be inconsistent with trends from adjacent locations and may suggest possible further data problems with these stations.

To improve reliability, records from periods longer than 30 years with at least 60% data coverage were selected and used to determine the regional relative sea level trend (Table 4). Similarly, trends of barometric pressure were determined for the sites (Table 5). These stations were

Table 1: Chart datum to land levelling datum corrections for South African tide gauge sites for the period 1998–2002

Port	Correction to be applied to chart datum tide levels (m)
Port Nolloth	+0.12
Saldanha	–0.15
Cape Town	–0.11
Simon's Town	–0.16
Hermanus	–0.19
Mossel Bay	–0.23
Knysna	–0.26
Port Elizabeth	–0.19
East London	–0.29
Durban	–0.20
Richards Bay	–0.19

Table 2: Height of chart datum relative to land levelling datum in South Africa. Corrected data conversions shown in bold

Port	Up to 31 Dec. 1978	1 Jan. 1979– 31 Dec.1997	1 Jan. 1998– 31 Dec.2002	1 Jan. 2003 onwards
Port Nolloth	–0.718*	–0.900	**–0.955**	–0.925
Saldanha	–0.582	–0.900	**–1.125**	–0.865
Cape Town	–0.829	–0.900	**–1.085**	–0.825
Simon's Town	–0.651	–0.900	**–1.163**	–0.843
Hermanus	–0.619	–0.900	**–1.168**	–0.788
Mossel Bay	–0.761	–0.900	**–1.393**	–0.933
Knysna	–0.625	–0.900	**–1.308**	–0.788
Port Elizabeth	–0.838	–0.900	**–1.216**	–0.836
East London	–0.762	–0.900	**–1.296**	–0.716
Durban	–0.838	–0.900	**–1.313**	–0.913
Richards Bay	–0.900	–0.900	**–1.395**	–1.015

* In use until 1 January 1994

Table 3: South African and Namibian uncorrected sea level trends. All stations are from the PSMSL data holdings except Durban (Mather 2007)

Tide station	Period of record	Years of record	Completeness of record (%)	Observed annual sea level trend using monthly data (mm y^{-1})	Observed annual sea level trend using annual data (mm y^{-1})
Walvis Bay	1958–1998	41	58	+0.38 ± 0.33	+0.67 ± 1.06
Lüderitz	1958–1998	41	78	+2.73 ± 0.81	+2.40 ± 1.64
Port Nolloth	1959–2007	49	75	+1.25 ± 0.23	+1.11 ± 0.41
Table Bay	1957–1972	16		Insufficient data	
Simon's Town	1957–2007	51	78	+1.58 ± 0.22	+1.14 ± 0.51
Granger Bay	1967–2007	41	77	+0.08 ± 0.20	+0.44 ± 0.53
Hermanus	1958–1964	7		Insufficient data	
Mossel Bay	1958–2007	50	77	–0.40 ± 0.19	–0.66 ± 0.56
Knynsa	1960–2007	48	64	+1.27 ± 0.50	+1.95 ± 1.62
Port Elizabeth	1978–2007	30	76	+2.97 ± 1.38	+2.89 ± 2.05
East London	1967–2007	41	50	+0.17 ± 0.05	–2.03 ± 1.86
Durban	1970–2003	34	79	+2.70 ± 0.05	+2.40 ± 0.29
Richards Bay	1990–2000	11		Insufficient data	

Table 4: Regional relative sea level trends. Equal weighting was given to each location in the calculation of regional sea level trends in each region

Region	Port	Observed annual sea level trend using monthly data (mm y^{-1})	Observed annual sea level trend using annual data (mm y^{-1})	Regional relative sea level trend based on the average of annual and monthly trends (mm y^{-1})
Western	Lüderitz	+2.73 ± 0.81	+2.40 ± 1.64	+1.87
	Port Nolloth	+1.25 ± 0.23	+1.11 ± 0.41	
Southern	Simon's Town	+1.58 ± 0.22	+1.14 ± 0.51	+0.68 or +1.48 (excluding Granger Bay and Mossel Bay)
	Granger Bay	+0.08 ± 0.22	+0.44 ± 0.53	
	Mossel Bay	–0.40 ± 0.19	–0.66 ± 0.56	
	Knynsa	+1.27 ± 0.50	+1.95 ± 1.62	
Eastern	Port Elizabeth	+2.97 ± 1.38	+2.89 ± 2.05	+2.74
	Durban	+2.70 ± 0.05*	+2.40 ± 0.29	

* Mather (2007)

Table 5: South African barometric level trends

Station	Period of record	Years of record	Completeness of record (%)	Observed monthly linear pressure trend (hPa month^{-1})	Observed annual linear pressure trend (hPa y^{-1})
Alexander Bay	1987–2006	20	89	–0.0160 ± 0.0034	–0.1630 ± 0.0521
Cape Town	1970–2006	37	95	–0.000395 ± 0.001200	+0.0073 ± 0.1220
George	1980–2006	27	95	–0.00384 ± 0.00175	–0.0566 ± 0.0157
Port Elizabeth	1978–2006	29	95	–0.00103 ± 0.00160	–0.0114 ± 0.0123
East London	1970–2006	37	98	+0.00221 ± 0.00110	+0.0281 ± 0.0074
Durban	1970–2006	37	97	+0.00277 ± 0.00162	+0.0304 ± 0.0071

analysed further to determine the extent of barometric pressure influence on sea level. These sea level trends were then barometrically corrected to provide an indication of the underlying rate of sea level change along the South African coastline. It should be noted that barometric stations are usually located at airports and can be situated several kilometres from the coastline. Ideally, the stations need to be adjacent to each other. However, because monthly or annual averages at the sites were used, the small variation between tide gauge and barometric station is assumed to be negligible or relatively constant between the sites.

To determine the proxy IB coefficients, monthly sea level recordings were correlated with monthly barometric pressure recordings (Figure 4). With the exception of Alexander Bay, the proxy IB coefficients compared well with the globally distributed IB coefficients derived by Hoar and Wilson (1994). The proxy IB coefficient for Alexander Bay of +3.60 mm hPa^{-1} implies that when barometric pressure increases sea level also increases. Although this trend is contrary to the established theory, it has been reported elsewhere (e.g. in the South Atlantic, Woodworth et al. 1995; in the Red Sea, El-Din et al. 2007) and may reflect specific local conditions. The derived proxy IB coefficient for Durban, which is at the same latitude as Alexander Bay, was used as an alternative. Hoar and Wilson (1994) showed that the IB coefficient is latitude-dependent, and that for southern Africa (28°–35° S) the expected values are between –5.3 mm hPa^{-1} and –6.9 mm hPa^{-1}. Using the derived barometric relationship, the sea level trends were corrected for barometric influences for the selected datasets and are shown in Tables 6 and 7.

In reviewing the vertical crustal movements from the Peltier ICE-5G model and the HartRAU GPS data, it was clear that the former model was relatively close to the actual recorded movements at Simon's Town, but it appeared to underestimate the movement farther east at Richards Bay (Table 8). In order to provide a specific vertical crustal movement value at each tide station, the vertical movement was distributed linearly along the East Coast between the two stations. Because no data are available for the West Coast, those for Simon's Town were used. This was done on the basis that, because the African plate is tilting upward in a south-west to north-east direction, the West Coast gauges would be approximately perpendicular to Simon's Town. The difference between the HartRAU data value estimated for Simon's Town and the Peltier model results for Port Nolloth and Saldanha was not significant, being only 0.09 mm y^{-1}.

The eustatic sea level trends were determined using the relative sea level trends corrected for barometric influences using Methods 1 and 2 (as detailed earlier). Vertical land movements were then taken into account and the resultant local and regional eustatic trends were determined (Tables 9 and 10).

At a regional level, sea levels are rising around the southern African coastline. For comparative purposes, the coastline was divided into the western, southern and eastern regions (Figure 1). The dissimilar physical factors between these regions could explain the differences found in sea level change.

Western region

This region contains one of four major coastal upwelling centres worldwide. The region is unique in that it is dominated by the cold upwelling waters of the Benguela system, which is trapped by warm waters to the north and

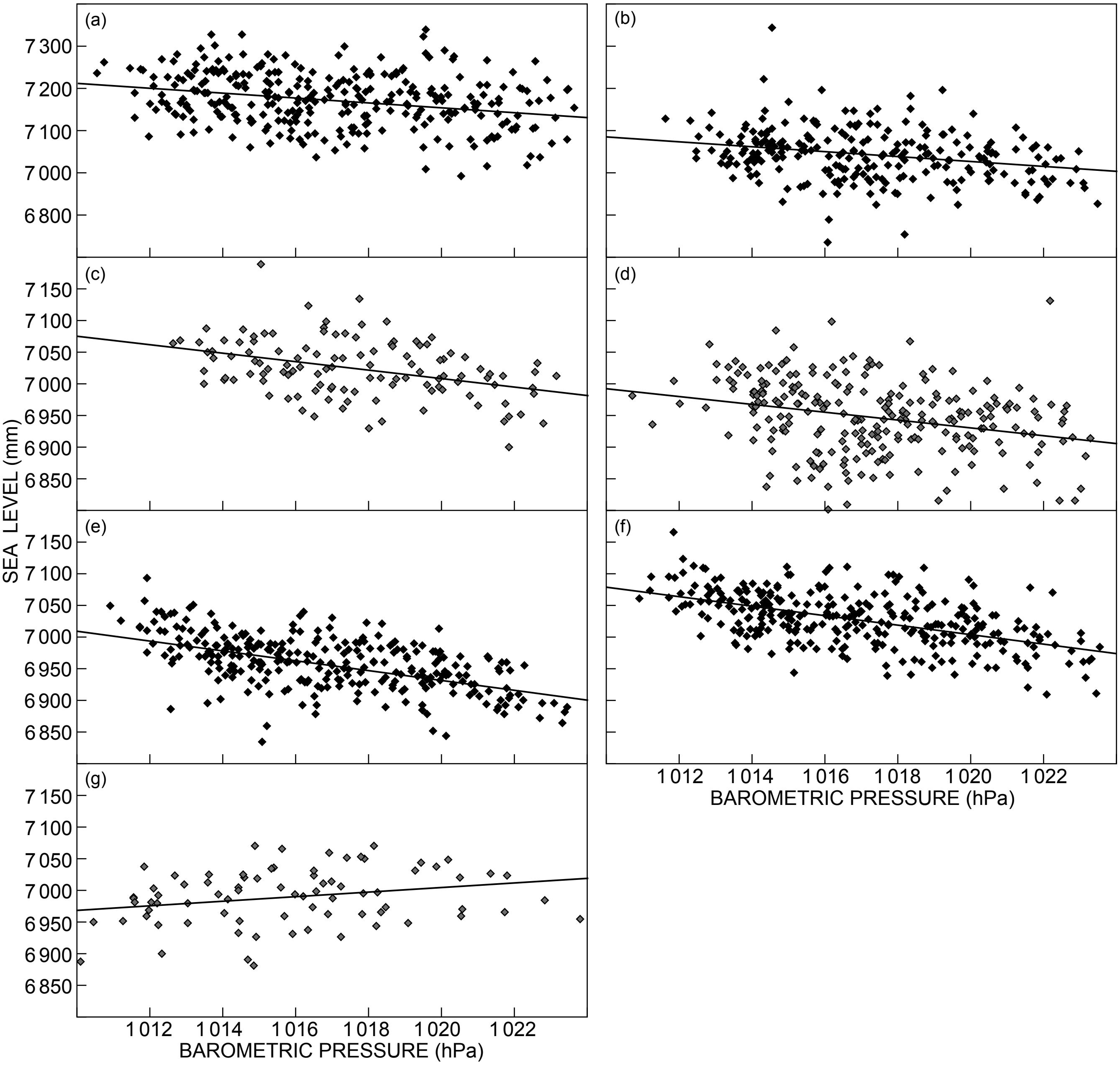

Figure 4: Relationship between sea level and barometric pressure, i.e. proxy IB coefficients for (a) Durban, (b) Port Elizabeth/Port Elizabeth, (c) George/Knysna, (d) George/Mossel Bay, (e) Cape Town/Granger Bay, (f) Cape Town/Simon's Town and (g) Alexander Bay/Port Nolloth

south (Shannon and O'Toole 2003). The western region is represented by three stations, Port Nolloth, Lüderitz and Walvis Bay. Unfortunately, the PSMSL does not have data for the past decade for these stations which reduces the period of analysis. As mentioned earlier, the sea level trend for Walvis Bay (+0.38 ± 0.33 mm y^{-1}) was excluded from the analysis because of concerns regarding the reliability of the data. The Port Nolloth and Lüderitz tide stations yielded a regional relative sea level trend of +1.87 mm y^{-1}. The barometric correction was not applied to Lüderitz owing to a lack of air pressure records at that station. However, the correction was applied to Port Nolloth, which yielded a sea level trend of between +0.76 mm y^{-1} and +0.13 mm y^{-1}. When vertical crustal movements were introduced, the eustatic sea level trend at Port Nolloth rose between +1.05 mm y^{-1} and +0.56 mm y^{-1}, with an average of +0.80 mm y^{-1}.

These trends appear to concur with the IPCC assessment of global sea level change when the contributions from ice melt and thermal expansion are considered. Global ice and glacier contributions have been estimated at +0.69 mm y^{-1} (glaciers and ice cap +0.5 ± 0.18 mm y^{-1}, Greenland ice sheet +0.05 ± 0.12 mm y^{-1} and Antarctic ice sheet +0.14 ± 0.41 mm y^{-1}) over a comparable period (to this study) of 1961–2003 (Bindoff et al. 2007). Thermal expansion of seawater has been found to be mainly confined to the upper layers of the ocean. Levitus et al. (2005) found that

Table 6: Barometrically corrected annual sea level trends using monthly data

Region	Station (tide gauge station/ weather station)	Observed annual sea level trend using monthly data (mm y^{-1})	Proxy IB coefficient (hPa y^{-1})	Method 1: summation of trends			Method 2: monthly barometrical corrected data
				Linear barometric trend (hPa y^{-1})	Resulting linear sea level trend (mm y^{-1})	Barometric-corrected linear sea level trend (mm y^{-1})	Barometric-corrected linear sea level trend (mm y^{-1})
Western	Port Nolloth/ Alexander Bay	+1.25 ± 0.23	–6.04 ± 6.59*	–0.163	–0.984	+0.27	+0.76 ± 1.11
Southern	Simon’s Town/ Cape Town	+1.58 ± 0.22	–7.51 ± 5.12	+0.007	+0.053	+1.63	+1.89 ± 0.34
	Granger Bay/ Cape Town	+0.08 ± 0.22	–7.67 ± 7.20	+0.007	+0.053	+0.03	+0.39 ± 0.20
	Mossel Bay/ George	–0.40 ± 0.19	–6.19 ± 8.21	–0.004	–0.020	–0.38	+0.22 ± 0.46
	Knysna/George	+1.27 ± 0.50	–6.73 ± 9.72	–0.006	–0.038	+1.23	+1.60 ± 0.76
Eastern	Port Elizabeth/ Port Elizabeth	+2.97 ± 1.38	–5.73 ± 8.04	–0.011	–0.063	+2.91	+3.38 ± 1.48
	Durban/Durban	+2.70 ± 0.05	–6.04 ± 6.59	+0.030	+0.180	+2.88	+2.63 ± 0.96

* Durban IB-value used

Table 7: Barometrically corrected annual sea level trends using annual data

Region	Station (tide gauge station/ weather station)	Recorded linear sea level trend using annual data (mm y^{-1})	Proxy IB coefficient (hPa y^{-1})	Method 1: summation of trends		
				Linear barometric trend (hPa y^{-1})	Resulting linear sea level trend (mm y^{-1})	Barometric-corrected linear sea level trend (mm y^{-1})
Western	Port Nolloth/ Alexander Bay	+1.11 ± 0.41	–6.04 ± 6.59*	–0.163	–0.984	+0.13
Southern	Simon’s Town/ Cape Town	+1.14 ± 0.51	–7.51 ± 5.12	+0.007	+0.053	+1.19
	Granger Bay/ Cape Town	+0.44 ± 0.53	–7.67 ± 7.20	+0.007	+0.053	+0.49
	Mossel Bay/ George	–0.66 ± 0.56	–6.19 ± 8.21	–0.004	–0.020	–0.64
	Knysna/George	+1.95 ± 1.62	–6.73 ± 9.72	–0.006	–0.038	+1.91
Eastern	Port Elizabeth/ Port Elizabeth	+2.89 ± 2.05	–5.73 ± 8.04	–0.011	–0.063	+2.83
	Durban/Durban	+2.40 ± 0.29	–6.04 ± 6.59	+0.030	+0.180	+2.58

* Durban IB-value used

most (69%) of the ocean warming has occurred in the upper 700 m over the period 1955–1998, a finding that was confirmed by Bindoff et al. (2007) for a slightly longer period of 1955–2003. Domingues et al. (2008) reported that 91% of the warming has occurred in the top 300 m. Reporting on the Benguela Current Large Marine Ecosystem, Shannon and O’Toole (2003) found a progressive warming of the surface waters of 0.7 °C from 1920 to 2003 in the Benguela region. This figure would induce a thermal expansion component of 0.51 mm y^{-1} (using a depth of 700 m of seawater and thermal expansion coefficient $\beta = 88 \times 10^{-6}$ m^3 K^{-1}) over a longer period than this analysis. The global thermal expansion component over the period 1961–2003 was estimated to be 0.42 ± 0.12 mm y^{-1} (Bindoff et al. 2007).

The combined contributions of global glacial and ice melt (+0.69 mm y^{-1}) and global thermal expansion (+0.42 mm y^{-1}) of +1.11 mm y^{-1} is similar to the rate of +0.80 mm y^{-1} derived in our study, and is in the lower end of the range of

Table 8: Vertical crustal movements along the southern African coastline

Station	ICE-5G VM2 model results (Peltier 2004) (mm y^{-1})	ICE-5G VM4 model results (Peltier 2004) (mm y^{-1})	HartRAU vertical crust movements for 2000–2007 (mm y^{-1})
Port Nolloth	+0.33	+0.21	+0.29*
Saldanha	+0.30	+0.20	+0.29*
Cape Town	+0.29	+0.19	+0.29*
Simon’s Town	+0.27	+0.18	+0.29 ± 0.18
Hermanus	+0.29	+0.20	+0.36$^{\$}$
Mossel Bay	+0.35	+0.25	+0.49$^{\$}$
Knysna	+0.34	+0.23	+0.54$^{\$}$
Port Elizabeth	+0.25	+0.15	+0.66$^{\$}$
East London	+0.23	+0.13	+0.78$^{\$}$
Durban	+0.21	+0.12	+1.03$^{\$}$
Richards Bay	+0.16	+0.08	+1.11 ± 0.25

* Same value as Simon’s Town used

$^{\$}$ Linear interpolation between Simon’s Town and Richards Bay

Table 9: Eustatic annual sea level trends using monthly data

Region	Station (tide gauge station/ weather station)	Recorded linear sea level trend relative to land (Table 3) (mm y^{-1})	Barometric-corrected linear sea level trend (Method 1 from Table 6) (mm y^{-1})	Barometric corrected linear sea level trend (Method 2 from Table 6) (mm y^{-1})	Vertical crustal movements from Table 8 (mm y^{-1})	Sea level corrected for vertical crustal movement and barometric changes (Method 1) (mm y^{-1})	Sea level corrected for vertical crustal movement and barometric changes (Method 2) (mm y^{-1})	Regional eustatic sea level change (mm y^{-1})
Western	Port Nolloth/ Alexander Bay	+1.25 ± 0.23	+0.27	+0.76 ± 1.11	+0.29 ± 0.18	+0.56	+1.05	+0.80
Southern	Simon's Town/ Cape Town	+1.58 ± 0.22	+1.63	+1.89 ± 0.34	+0.29 ± 0.18	+1.92	+2.18	+1.23 or +2.00 (excluding Granger Bay and Mossel Bay)
	Granger Bay/ Cape Town	+0.08 ± 0.22	+0.03	+0.39 ± 0.20	+0.29 ± 0.18	+0.32	+0.68	
	Mossel Bay/ George	–0.40 ± 0.19	–0.38	+0.22 ± 0.46	+0.49	+0.11	+0.71	
	Knysna/ George	+1.27 ± 0.50	+1.23	+1.60 ± 0.76	+0.54	+1.77	+2.14	
Eastern	Port Elizabeth/ Port Elizabeth	+2.97 ± 1.38	+2.91	+3.38 ± 1.48	+0.66	+3.57	+4.04	+3.75
	Durban/ Durban	+2.70 ± 0.05	+2.88	+2.63 ± 0.96	+1.03	+3.73	+3.66	

Table 10: Eustatic sea level trends using annual sea level data

Region	Station (tide gauge station/ weather station)	Recorded annual sea level trend (Table 3) (mm y^{-1})	Barometric-corrected linear sea level trend (Method 1 from Table 7) (mm y^{-1})	Vertical crustal movements from Table 8 (mm y^{-1})	Sea level corrected for vertical crustal movement and barometric changes (Method 1) (mm y^{-1})	Regional eustatic sea level change (mm y^{-1})
Western	Port Nolloth/ Alexander Bay	+1.11 ± 0.41	+0.13	+0.29 ± 0.18	+0.42	+0.42
Southern	Simon's Town/ Cape Town	+1.14 ± 0.51	+1.19	+0.29 ± 0.18	+1.48	+1.14 or +1.97 (excluding Granger Bay and Mossel Bay)
	Granger Bay/ Cape Town	+0.44 ± 0.53	+0.49	+0.29 ± 0.18	+0.78	
	Mossel Bay/ George	–0.66 ± 0.56	–0.64	+0.49	–0.15	
	Knysna/ George	+1.95 ± 1.62	+1.91	+0.54	+2.45	
Eastern	Port Elizabeth/ Port Elizabeth	+2.89 ± 2.05	+2.83	+0.66	+3.49	+3.55
	Durban/ Durban	+2.40 ± 0.29	+2.58	+1.03	+3.61	

0.8–1.6 mm y^{-1} provided by Ishii et al. (2006). The eustatic sea level result of +0.42 mm y^{-1} using annual data appears to be low, which may have been influenced by the limited annual sea level data. Also, the large negative barometric trend recorded at Alexander Bay appears questionable. Unfortunately, this is the only sea pressure gauge in the area so it is difficult to confirm this result. The HadSLP2 data trends given in Gillett et al. (2005) also reflect a negative trend for this grid location. This negative trend, however, at Alexander Bay should be viewed with caution.

Southern region

This region forms the south-eastern extreme of the Benguela system and upwelling has been observed seasonally as far east as Port Elizabeth (Shannon and O'Toole 2003). The region is subject to variability in water temperature because of the mixing of the Benguela and Agulhas currents. Based on the work of Levitus et al. (2005), Bindoff et al. (2007) noted a significant warming off Cape Town and cooling off Mossel Bay/Knysna over the period 1955–2003. It is postulated that these two warm and cool seawater nodes are non-stationary and, depending on the relative strength of the Benguela and Agulhas currents, these nodes flux in an east/west and onshore/offshore direction, adding to the variability of the region.

There are four suitable gauge sites along the coastline of the southern region (Figure 1), which provides better coverage in the calculation of regional sea level changes than in the western region. Three of the tide gauges recorded rising sea levels, whereas the one at Mossel Bay recorded a change of –0.40 ± 0.19 mm y^{-1}. This difference appears to be at odds with surrounding stations and previous measurements for Mossel Bay (i.e. +1.01 mm y^{-1}) for the period 1960–1988 (Brundrit et al. 1989). The tide records of Mossel Bay and Knysna, situated approximately 105 km apart, were examined in more detail (Figure 5). The two gauges should record similar sea levels because of their close proximity, but there may be small differences due to dissimilarities between the sites. For example, Knysna may be affected by the dynamics at the mouth of the lagoon due to the Knysna Heads. The records at Mossel Bay show a drop in sea levels of approximately 100 mm for the period 1991–1995. If this period is removed from the records, then Mossel Bay shows little sea level change. The tide gauge records at Knysna is similarly affected, but at different times. Knysna has two drops in sea level of similar magnitude for the periods 1969–1972 and 1978–1979, and a rise of approximately 80 mm for the period 1996–2008. Removal of these periods from the record reduces the dataset to such an extent that trend estimates are not reliable. These variations are not temporally synchronised at both tide gauges so they are not the result of large-scale oceanic processes. These drops in sea level could be a result of data or gauge errors, which will require further investigation to improve the quality of the data.

The stations of Simon's Town and Knysna yielded a regional barometrically corrected sea level change of +1.48 mm y^{-1}. When vertical crustal movements were factored in, the regional eustatic sea level trends were +1.97 mm y^{-1} and +2.00 mm y^{-1} respectively. The eustatic sea level change was higher in the warmer southern region than in the cooler western region.

Eastern region

This region is affected by the warm Agulhas Current which moves southwards along the coastline. The warm water is mainly near the surface, which has been exposed to rising air temperatures in the equatorial zone. There are four tide gauge stations along this coastline. Because data from Richards Bay were only over an 11-year period and those from East London had just 50% coverage, they were excluded from the analysis. The average regional sea level change rate of +3.03 mm y^{-1} estimated for this region was the highest found along the South African coastline. Correcting for local influences of barometric pressure at Port Elizabeth and Durban results in both stations recording a marginally higher rate of sea level change than the uncorrected sea level trends. Those at Port Elizabeth ranged from +2.83 mm y^{-1} to +3.38 mm y^{-1} and at Durban from +2.58 mm y^{-1} to +2.88 mm y^{-1}. At both stations, increasing barometric trends

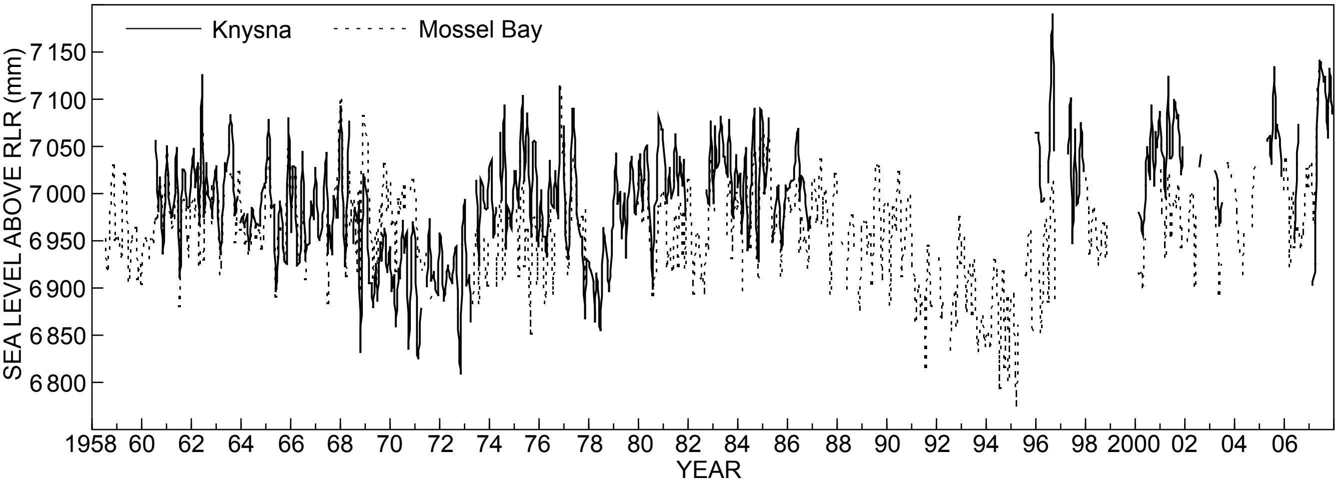

Figure 5: Tide records for Knysna and Mossel Bay, 1958–2008

suppress sea level changes to varying degrees, specifically in Durban, by as much as +0.18 mm y^{-1}. When these sea level trends were adjusted for vertical crustal movements, the regional eustatic sea level trends ranged between +3.55 mm y^{-1} and +3.75 mm y^{-1}. These figures are greater than the global average of +3.0 mm y^{-1} (Bindoff et al. 2007), which is to be expected for a region that is driven by warm water feeding in from the equator.

Conclusion

This is the first study to investigate all tide gauge sites along the southern African coastline and to assess the problems associated with the tidal records. It also considers for the first time the effects of barometric pressure and vertical crustal movements on sea level trends along the coastline. Several problems with the SAN tide dataset have been identified, which need to be rectified using corrections derived from this study. Over the past 50 years, sea level change around the southern African coastline has not been constant, thus it would be incorrect to apply a globally calculated sea level rise value uniformly to that coastline. The regional sea level trends determined here can be applied with more confidence to the various sections of our coastline for integrated coastal zone planning, including adaptation to sea level rise as well as coastal infrastructure planning. The variations in sea level change around the coast show distinctive differences in response, depending on their location. These changes are principally driven by a combination of physical characteristics at each location, most notably by the influences and interactions of the Agulhas and Benguela currents, and in turn by water temperature, barometric air pressure changes and vertical crustal movements. Whether these results reflect long-term trends or are part of a shorter cycle will be better understood when more data are accumulated in the future.

Acknowledgements — We acknowledge the data generously provided by the South African Weather Service, the South African Navy's Hydrographic Office, the Permanent Service for Mean Sea Level, and by Prof. WR Peltier and Dr L Combrinck of the Hartebeesthoek Radio Astronomy Observatory.

References

Baker TF. 1993. Absolute sea level measurements, climate change and vertical crustal movements. *Global and Planetary Change* 8: 149–159.

Bell RG, Goring DG, de Lange WP. 2000. Sea level change and storm surge in the context of climate change. *IPENZ Transactions* 27, No. 1/Gen.

Bindoff NL, McDougall JT. 2000. Decadal changes along an Indian Ocean section at 32S and their interpretation. *Journal of Physical Oceanography* 30: 1207–1222.

Bindoff NL, Willebrand J, Artale V, Cazenave A, Gregory J, Gulev S, Hanawa K, Le Quéré C, Levitus S, Nojiri Y, Shum CK, Talley LD, Unnikrishnan A. 2007. Observations: oceanic climate change and sea level. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds), *Climate change 2007: the physical science basis.* Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. pp 385–432.

Brundrit GB. 1984. Monthly mean sea levels along the west coast of southern Africa. *South African Journal of Marine Science* 2: 195–203.

Brundrit GB. 1995. Trends of southern African sea level: statistical analysis and interpretation. *South African Journal of Marine Science* 16: 9–17.

Brundrit GB, Hughes P, Shillington FA. 1989. Sea level rise scenarios for South Africa. Cape Town: Sea Level Research Group, Department of Oceanography, University of Cape Town.

Church JA, Gregory JM, Huybrechts P, Kuhn M, Lambeck K, Nhuan MT, Qin D, Woodworth PL et al. 2001. Changes in sea level. In*:* Douglas BC, Ramirez A (eds), *Climate change 2001: the scientific basis.* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. pp 639–693.

Cooper JAG. 1995. Shoreline changes on the Natal coastline: Mkomazi river mouth to Tugela river mouth. Pietermaritzburg: Natal Town and Regional Planning Report, Vol. 77.

Davis JL, Mitrovica JX. 1996. Glacial isostatic adjustment and the anomalous tide gauge record of eastern North America. *Nature* 379: 331–333.

Dickman SR. 1988. Theoretical investigation of the oceanic inverted barometer response. *Journal of Geophysical Research* 93: 14941–14946.

Domingues CM, Church JA, White NJ, Glecker PJ, Wijffels SE, Barker PM, Dunn JR. 2008. Improved estimates of upper-ocean warming and multi-decadal sea level rise. *Nature* 453: 1090–1094.

Doodson AT. 1924. Meteorological perturbations of sea level and tides. *Monthly Notices of the Royal Astronomical Society*, Geophysical Supplement 1: 124.

Douglas BC. 1991. Global sea level rise. *Journal of Geophysical Research* 96(C4): 6981–6992.

Dyurgerov MB, Meier MF. 1997. Year-to-year fluctuations of global mass balance of small glaciers and their contribution to sea level changes. *Arctic and Alpine Research* 29: 392–402.

El-Din KA, Abdelrahman SM, El Meligy M. 2007. Seasonal and long term variations of sea level and meteorological conditions along the Egyptian coasts. In: Ozhan E (ed.), *Proceedings of the eighth international conference on the Mediterranean coastal environment, MEDCOAST 07, November 2007*, *Alexandria, Egypt*. *Vol. 2*. Ankara: Middle Eastern Technical University. pp 1295–1307.

Garland G, Mather AA. 2007. Recent sea level change at Durban and implications for management. *Proceedings of the eighth international conference on the Mediterranean coastal environment MEDCOAST 07, November 2007, Alexandria, Egypt*. *Vol. 2*. Ankara: Middle Eastern Technical University. pp 1309–1319.

Gillett NP, Zwiers FW, Weaver AJ, Stott PA. 2003. Detection of human influence on sea level pressure. *Nature* 422: 292–294.

Gornitz V. 2000. Impoundment, groundwater mining and other hydrologic transformations: impacts on global sea level rise. In: Douglas BC, Kearney MS, Leatherman SP (eds), *Sea level rise: history and consequences*. Amsterdam: Academic Press. pp 97–119.

Hoar TJ, Wilson CR. 1994. Geosat observations of sea level response to barometric pressure forcing. *Geophysical Research Letters* 21(23): 2515–2518.

Hughes P, Brundrit GB, Shillington FA. 1991. South African sea level measurements in the global context of sea level rise. *South African Journal of Science* 87: 447–453.

IPCC (International Panel on Climate Change). 1990. Climate change. In: Houghton JT, Jenkins GJ, Ephraums JJ (eds), *The IPCC scientific assessment.* Cambridge: Cambridge University Press. pp 257–281.

IPCC (International Panel on Climate Change). 1996. *The IPCC second assessment: climate change 1995*. Cambridge: Cambridge University Press.

IPCC (International Panel on Climate Change). 2001. Third Assessment Report. In: Church JA, Gregory JM (eds), *Changes in sea level.* Cambridge: Cambridge University Press. pp 639–693.

Ishii M, Kimoto M, Sakamoto K, Iwasaki SI. 2006. Steric sea level changes estimated from historical ocean subsurface temperature and salinity analyses. *Journal of Oceanography* 62: 155–170.

Levitus S, Antonov JI, Boyer TP. 2005. Warming of the world ocean, 1955–2003. *Geophysical Research Letters* 32: LO2604.

Mather AA. 2008. Sea level rise for the east coast of Southern Africa. Paper No. M-04 presented at COPEDEC VII, Dubai, UAE.

Mather AA. 2007. Linear and nonlinear sea level changes at Durban, South Africa. *South African Journal of Science* 103: 509–512.

Mitchum GT. 1998. Monitoring the stability of satellite altimeters with tide gauges. *Journal of Atmospheric and Oceanic Technology* 15: 721–730.

Nerem RS, Haines BJ, Hendricks J, Minister JF, Mitchum GT, White WB. 1997. Improved determination of mean sea level using TOPEX/POSEIDON altimeter data. *Geophysical Research Letters* 24: 1331–1334.

Peltier WR. 1994. Ice-age paleotopography. *Science* 265: 195–210.

Peltier WR. 2004. Global glacial isostacy and the surface of the ice-age earth: The ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Science* 32: 111–149.

Pirazzoli PA, Stiros SC, Arnold M, Laborel J, Laborel-Deguen F, Papageorgian S. 1994. Episodic uplift deduced from Holocene shorelines in the Perachora Peninsula, Corinth area, Greece. *Tectonophysics* 229: 201–209.

Ponte RM. 1994. Understanding the relationship between wind- and pressure-driven sea level variability. *Journal of Geophysical Research* 99(C4): 8033–8039.

Ponte RM. 2006. Low frequency sea level variability and the inverted barometer effect. *Journal of Atmospheric and Oceanic Technology* 23: 619–629.

Proshutinsky A, Ashik IM, Dvorkin EN, Häkkinen S, Krishfield RA, Peltier WR. 2004. Secular sea level change in the Russian sector of the Arctic Ocean. *Journal of Geophysical Research* 109: 1–19.

Pugh D (ed.). 1987. *Tides, surges and mean sea level.* New York: John Wiley and Sons.

Pugh D (ed.). 2004. *Changing sea levels. Effects of tides, weather and climate.* Cambridge: Cambridge University Press.

Ramsay PJ, Cooper JAG. 2002. Late Quaternary sea-level change in South Africa. *Quaternary Research* 57: 82–90.

Roden GI. 1966. Low-frequency sea level oscillations along the Pacific coast of North America. *Journal of Geophysical Research* 71: 4755–4776.

Roden GI, Rossby HT. 1999. Early Swedish contribution to oceanography: Nils Gissler (1715–71) and the inverted barometric effect. *Bulletin of the American Meteorological Society* 80: 675–682.

Rossiter JR. 1962. Long-term variations in sea level. In: Hill MN (ed.), *The sea, vol. 1.* New York: Wiley-Interscience. pp 590–610.

SAN (South African Navy). 2008. *2008 South African tide tables*. South African Navy Publishing Unit.

Shannon LV, O'Toole M. 2003. Sustainability of the Benguela: ex Africa semper aliquid novi. In: Hempel G, Sherman K (eds), *Large marine ecosystems of the world: trends in exploitation, protection and research*. Amsterdam: Elsevier. pp 227–253.

Singh A, Aung T. 2005. Effect of barometric pressure on sea level variations in the Pacific Region. *The South Pacific Journal of Natural Science* 23: 9–15.

Schönwiese C-D, Rapp J (eds). 1997. *Climate trend atlas of Europe based on observations 1891–1990.* Dordrecht: Kluwer Academic Publishers.

Schönwiese C-D, Rapp J, Fuchs T, Denhard M. 1994. Observed climate trends in Europe 1891–1990. *Meteorologische Zeitschrift* 3: 22–28.

Warrick RA, Le Provost C, Meier MF, Oerlemans J, Woodworth PL. 1996. Changes in sea level. In: Houghton JT, Meira Filho LG, Callander BA, Harris N, Klattenberg A, Maskell K (eds), *Climate change 1995, the science of climate change.* Cambridge: Cambridge University Press. pp 359–405.

Woodworth PL. 1987. Trends in U.K. mean sea level. *Marine Geodesy* 11: 57–87.

Woodworth PL. 1990. A search for accelerations in records of European mean sea level. *International Journal of Climatology* 10: 129–143.

Woodworth PL, Aman A, Aarup T. 2007. Sea level monitoring in Africa. *African Journal of Marine Science* 29: 321–330.

Woodworth PL, Windle SA, Vassie JM. 1995. Departures from the local inverse barometer model at periods of 5 days in the central South Atlantic. *Journal of Geophysical Research* 100(C9): 18281–18290.

Wunsch C, Stammer D. 1997. Atmospheric loading and the oceanic "inverted barometer" effect. *Review of Geophysics* 35: 79–107.