LaquaR Consultants CC

P.O. Box 474
Eppindust
Cape Town 7475
South Africa

Cell: +27 (0)73 511 1717
Tel: +27 (0)21 510 6160
Email: lucindafairhurst@gmail.com

Global Climate Change and Adaptation – A Sea-Level Rise Risk Assessment.

PROPOSAL NUMBER:
R030800032
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GLOBAL CLIMATE CHANGE

Prepared For:
The City of Cape Town
Environmental Resource Management Department

CITY OF CAPE TOWN | ISIXEKO SASEKAPA | STAD KAAPSTAD

THIS CITY WORKS FOR YOU

Phase one:
Sea Level Rise Model
Report prepared by Prof. Geoff Brundrit
March 2008

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The scientific evidence is now overwhelming: climate change presents very serious risks, and it demands an urgent global response. *Stern Review 2007*

A storm swell, coinciding with a Saros spring high tide, struck the Kwa Zulu Natal coast on 19/20 March 2007. At its peak, the storm produced swells of ~8.5m, caused significant coastal erosion and unprecedented damage to coastal property, estimated at more than one billion rand. *Smith et al 2007*

Coasts are projected to be exposed to increasing risks, including coastal erosion, due to climate change and sea level rise. The effect will be exacerbated by increasing human pressure on coastal areas. *IPCC Fourth Assessment Report Feb 2007*

Sea level will rise between 18 and 59cm by 2100. *IPCC AR4 Feb 2007*

I find it almost inconceivable that "business-as-usual" climate change will not result in a rise in sea level measured in metres within a century. *James Hansen NASA July 2007*

It became apparent that, concerning the melting of the Greenland and Antarctic ice sheets, we really don't know enough. *Rajendra Pachauri, IPCC Chair Nov 2007*

The 2007 melting season set a new record for snowmelt over the Greenland ice sheet.

EOS 25 Sep 2007

Arctic sea ice declined rapidly to unprecedented low extents in the summer of 2007.

EOS 8 Jan 2008

Current models suggest virtually complete elimination of the Greenland ice sheet and a resulting contribution to sea level of about 7m if global average warming were sustained for millennia in excess of 1.9 to 4.6 degrees Celsius relative to pre-industrial values.

IPCC Synthesis Report Nov 2007

The benefits of strong early action on climate change outweigh the costs.

Stern Review 2007

INTRODUCTION

The City of Cape Town have awarded LaquaR Consultants CC the contract for their Proposal Number: R03-404/06-07

Reference: Global Climate Change

Date: January – July 2008.

An extract from the Terms of Reference of the contract, relevant to this first Phase One, now follows.

TERMS OF REFERENCE

Global Climate Change: Coastal Climate Change and Adaptation - A Sea-Level Rise Risk Assessment for the City of Cape Town

1. Background and Introduction:

The City of Cape Town administers approximately 307 km of coastline, arguably its single greatest economic and social asset. In October 2003 the City formally adopted a Coastal Zone Management Strategy with the intention of managing and safeguarding the coastal asset for current and future generations.

The City's coast provides a range of social and economic opportunities including recreational and amenity areas, sought after housing and development opportunities as well as core economic attributes. In addition, the City's coast is a dynamic ecological system that supports a wide range of species, ecological systems and ecological services.

Global climate change predictions suggest that amongst others, sea level rise and an increase in the intensity and frequency of storm events may have significant impact on coastlines across the globe. Cape Town with its extensive coastline may be particularly vulnerable to these predicted changes.

2. Motivation and Aim of Project

The aim of the Sea-Level Rise Risk Assessment Project is to:

- Model the predicted sea-level changes in a range of scenario's (time series, incremental climate change, shear events, and storm frequency and intensity).
- Model the form that those changes will take.
- Understand the associated impacts on existing coastal systems, infrastructure and property
- Provide guidance and implications to future coastal development (to be included in the City's Coastal Development Guidelines)
- Identify high risk areas that are prone to high impact
- Begin to understand and develop long-term mitigation measures.

The primary objective of this study is therefore:

To model and understand the ramifications of predicted sea-level rise and increased storm events for the City of Caped Town, thereby providing information that may be used for future planning, preparedness and risk mitigation.

3. Project Phases

The project will be undertaken in four distinct phases. Each phase of the project will provide specific outcomes and deliverables.

Phase One: Climate Change Sea-Level Rise Model

Phase one of the project will model the predicted sea-level changes in a range of scenarios. A computer based GIS model will be developed that will demonstrate the coastal changes resulting from sea-level rise. The model must be developed in such a way that variables within the model may be changes to accommodate variations within predictions as well as illustrate the impacts of catastrophic and combined events. The GIS model must make use of existing climate and climate change models, the City's aerial photography and survey data, contour maps and infrastructure information (hard and soft coastal edges).

The model must be designed to incorporate and demonstrate, at a minimum, the following information:

- Time series: Show changes over time within a 5-100 year horizon based on best available climate change predictions.
- Demonstrate the impacts of sea-level rise based on incremental change in climate patterns
- Demonstrate the impacts of sea-level rise based on shear events, i.e. dramatic and immediate change in sea-levels.
- Demonstrate the impacts of combination events (i.e. sea-level rise combined with spring high tide, a storm event coupled with a high rainfall event).

- Model and demonstrate the form that these changes will take, taking into account the different coastal edges (hard man-made surfaces such as the Sea Point Promenade, rocky shores, sandy beaches and coastal estuaries).

In order to achieve the **Phase One: Climate Change Sea Level Rise Model** requirements, the following approach is taken.

- Review the nature of extreme sea level events along the coastline of the City of Cape Town, so as to establish the various contributions/components/constituents that might evolve under the effects of climate change. This will be achieved through a re-interpretation of sea level records from the SA Navy Tidal Network stations at Simon’s Town and Cape Town. This forms the **First Study**, which provides a **Present Day Very Worst Case Scenario** of extreme sea levels for use in the GIS Inundation Model for the coastline of the City of Cape Town.

- Review global projections of the influence of climate change on sea level, as given in studies such as the recent Assessment Reports of the Inter-Governmental Panel on Climate Change. This will provide estimates of the influence of climate change on local constituents of sea level in the vertical, as a series of projections on decadal and centennial scales, together with their range of uncertainties. The **Second Study** gives estimates of sea level rise for the coastline of the City of Cape Town in the near future, and provides the **Scenario at the End of the Next Decade** for the GIS model. The **Third Study** focuses on the much more uncertain longer term situation when wholesale ice melting is expected to lead to greatly enhanced sea level rise, and provides the **Polar Ice Sheet Melt Scenario** and its effects on the coastline of the City of Cape Town on century time scales.

- Build these projections of sea level rise into the Geographic Information System (GIS) terrain model of the metropolitan area, maintained by the Geomatics Department of the City of Cape Town. This will generate illustrative scenarios of future inundation of coastal land, and the identification of vulnerable locations. Overlays of the infrastructure and services within the GIS model will then begin to highlight the potential negative consequences of climate change from inundation in these vulnerable locations.

THE FIRST STUDY

EXTREME SEA LEVELS ALONG THE COASTLINE OF THE CITY OF CAPE TOWN

There is concern about the impact of extreme sea levels on infrastructure and services along the coastline of the City of Cape Town, especially with the threats of sea level rise and increased storminess associated with global warming. The purpose of this first study is to summarise what is known about present day sea levels, with an emphasis on extreme events and on particularly vulnerable sections of the coastline. Once this study is complete, it will be possible to shift the focus onto the implications of the future addition of sea level rise to the situation.

There are essentially three factors that contribute to present day sea level: tides, weather effects and wave set-up, though the last mentioned only affects surf zones. They have different characteristics, so the three factors need to be carefully combined to assess their total contribution and potential impact. The material relevant to the coastline of the City of Cape Town is extracted and embellished in this study.

The Tides

The tides are completely predictable and affect the entire coastline in a uniform way. However, tidal heights vary on a daily, fortnightly, seasonal and on a year to year basis. The detail is provided in the Tide Tables published on an annual basis by the

Hydrographic Office of the South African Navy, and the information for Granger Bay (Table Bay) and Simon's Bay (False Bay) is particularly relevant to this study.

In this study, the Land Levelling Datum (LLD), rather than Chart Datum (CD), is used as a baseline for all heights and levels, so that they are immediately recognizable by the Geographic Information System Inundation Model being developed by the City of Cape Town. The relationship between LLD and CD over the years is tabulated in the Tide Tables.

Tidal Characteristics	Simon's Bay	Granger Bay
Mean Tide Level (MTL)	LLD+16cm	LLD+15cm
Mean High Water Neaps (MHWN)	LLD+44cm	LLD+43cm
Mean High Water Springs (MHWS)	LLD+90cm	LLD+86cm
Highest Astronomical Tide (HAT)	LLD+124cm	LLD+120cm

In summary the tides for these two ports are very similar, so that it is possible to use the longer and more reliable information from Simon's Bay as being representative of the entire coast of the City of Cape Town.

Within each fortnight between full moon and new moon, high tide over the days of neap tide typically only reaches levels of 44cm above LLD whilst, over the days of spring tides, the high tide reaches 90cm above LLD. The overall maximum spring high tide is much higher, being the Highest Astronomical Tide at LLD+124cm. The tide does not reach HAT every year. HAT is the maximum tidal height reached in the 18.6 year cycle of the precession of the Moon's ascending node (also known as the Saros cycle). The mean for the other tidal measures is also taken over this long 18.6 year cycle time.

When it comes to extreme tides, only high water at spring tides occurring around the time of full and new moon, rather than at neap tides, need to be taken into account. These spring high tides exhibit great variability in height, but have a regular pattern (the equinoctial, lunar perigee and Saros cycles) over the long term. In any given year, the spring high tides peak in the seasons of spring and autumn as part of the equinoctial cycle, so that the Highest Astronomical Tide of the Year (HATOY) will occur in one of the months within spring or autumn. HATOY will also be higher in those years when the Moon's perigee occurs in spring or autumn, which happens every 4.4 years. Finally HATOY will reach HAT in the peak year of the Saros cycle.

The values and times of HATOY at Simon's Bay in recent years are tabulated to illustrate this.

Year	HATOY	Time and Date
2003	HAT-6cm	O4h29 Mar 20
2004	HAT-11cm	03h39 Apr 6
2005	HAT-8cm	04h16 Feb 10
2006	HAT-1cm	04h10 Mar 1
2007	HAT-2cm	03h57 Mar 20
2008	HAT-10cm	03h50 Apr 7

The highest tides are restricted to a few hours on particular days in particular months in particular years and are completely predictable. If the tides are the determining factor in extreme sea level (*Searson and Brundrit 1995*), it will be important to note these times of particular vulnerability. The dates and times and heights can be extracted from the Tide Tables, which are published each year by the Hydrographer of the South African Navy.

The Weather Effect

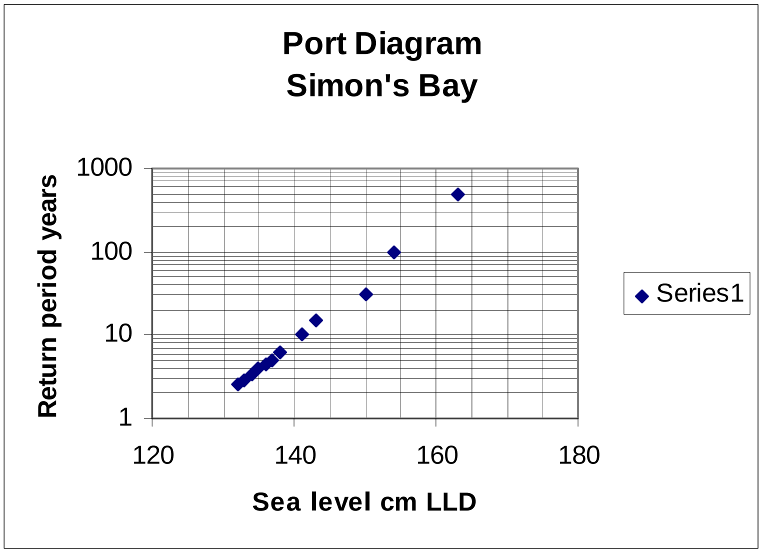
The effect of passing synoptic weather systems means that observed sea level can be higher than the predicted tide when the air pressure is low and when the wind piles the water up against the coast (passing mid-latitude depressions; low pressure systems; cold fronts). As with the tides, the entire coastline is affected. Synoptic weather effects last for two or three days, but their predictability is limited to little more than one week. Forecasts of severe weather are issued by the South African Weather Service.

While individual depressions do vary in their intensity and duration, their statistical characteristics vary little from season to season or from year to year. An overall description can be obtained from a 30 year record of hourly observations of sea level from Simon's Bay between 1960 and 1990 (*Searson and Brundrit 1995*). The almost 250 000 hourly deviations of sea level from the predicted tide, due to the synoptic weather effect, form an essentially normal distribution with a standard deviation of 8.2cm.

For further study of the extreme values, the deviations can be grouped into monthly maxima for each month of the 30 year period. The overall monthly maximum deviation in the 30 year record was + 39cm, whilst in 15 of the 360 monthly maxima, the deviation exceeded +25cm. The spread of these extreme monthly maximum deviations was not uniform over the three decades. Three occurred in the 1960s, two in the 1970s and the remaining ten were in the 1980s. Whilst this might suggest that there is a tendency towards increasing storminess, it should be noted that the overall maximum deviation of +39cm occurred in August 1963.

Sea Level

The 30 year record of observations of sea level can be analysed for extremes of the joint effect of tides and weather on sea level around the coast of the City of Cape Town. Such an analysis gives the mean sea level as LLD+17cm, with a 30 year maximum sea level of LLD+150cm. The 30 year observed maximum sea level at Simon's Bay occurred on 25 September 1981, on a peak spring high tide with a height of LLD+119cm and an extreme storm with a deviation of +31cm. Indeed the seven highest observed sea levels at Simon's Bay in this thirty year period all coincided with near equinoctial spring high tides, emphasizing the enhanced vulnerability from such events. Although this 30 year maximum sea level exceeds HAT, it does not approach the level of (LLD+124) + 39cm, or LLD+163cm, which would be achieved on the simultaneous occurrence of HAT (an 18.6 year tide event) and a 30 year storm event. Such a joint extreme event has a return period of some 500 years. A Port Diagram showing the detailed return periods for extreme sea levels at Simon's Bay is shown in *Searson and Brundrit 1995*, whilst a simplified Port Diagram, based on annual maxima, follows.



The observed annual maximum sea levels are used in the Simon's Bay Port Diagram for return periods up to 30 years, whilst the sea levels of LLD+154cm at a return period of 100 years and LLD+163cm for a return period of 500 years are extrapolations for illustration.

KZN Storm of March 2007

The simultaneous occurrence of a tidal height close to HAT and an estimated 30 year storm occurred along the coast of Kwa Zulu Natal in the early hours of 19 March 2007 (*Smith, Guastella, Bundy and Mather 2007*). The measurements taken at that time provide a valuable resource for confirming the approach taken for the coast of the City of Cape Town, and for suggesting values that should be used on exposed coasts.

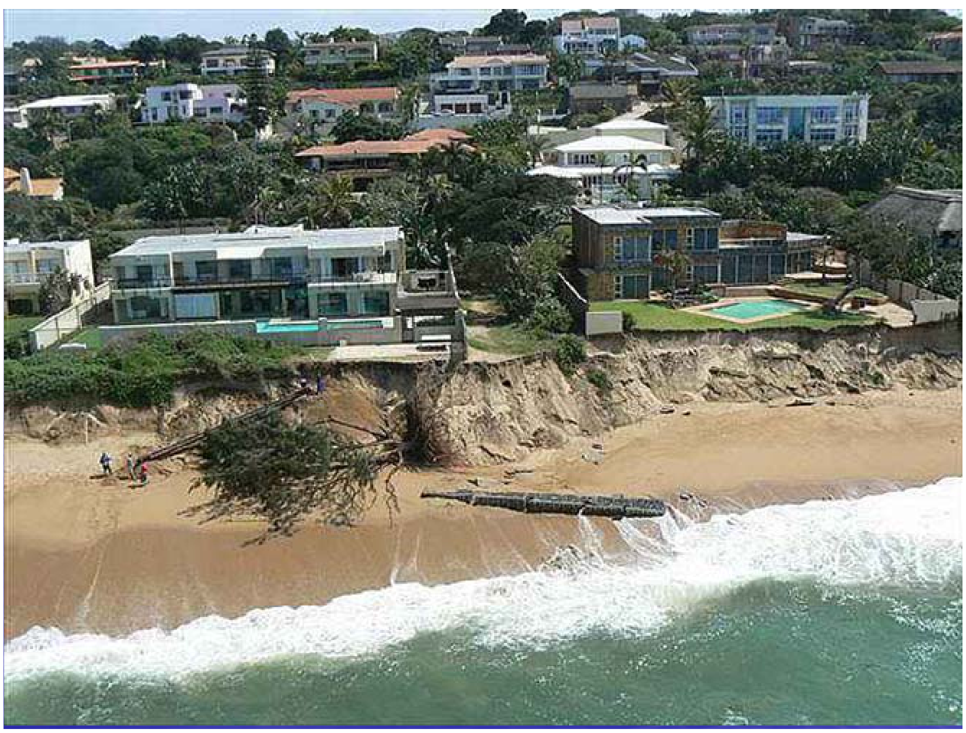
The Highest Astronomical Tide for Durban is LLD+139cm. A ten year record of sea level observations from Durban from 1980-1990 again shows the deviation of observed sea level from the predicted tide to be normally distributed, with a standard deviation of 10.3cm (*Searson and Brundrit 1995*). The maximum deviation over the ten years gives an extra height of +37cm. The simultaneous occurrence of HAT and a ten year storm leads to a sea level of LLD+176cm with a return period of some 180 years. By contrast, the earlier ten year record of sea level observations gives a maximum sea level of LLD+159cm.

Turning to the situation on the KZN coast early on the morning of 19 March 2007, the observed sea level was LLD+188cm. The predicted early morning high tide for 19 March was only LLD+133cm, giving a contribution from the storm of +55cm. Such an extreme storm probably has a return period approaching 100 years. It should be noted that the predicted tide for the next day, early morning on 20 March 2007 was the HATOY for

2007 at LLD+137cm. If the storm had persisted or occurred at that time, the observed sea level would have been LLD+192cm and even greater damage would have been caused.

Wave Set-up and Storm Impact

The effect of wave set-up can now be summarized. This occurs due to interactions in the surf zone, where there is an increase in the water level leading to more vigorous run-up in the swash and intensified erosion of dune faces and other soft material. Measurements were made during the storm on the KZN coast in the early morning of 19 March 2007, and are reported in *Smith, Guastella, Bundy and Mather (2007)*. Referring these measurements to Land Levelling Datum rather than Chart Datum, the landward edge of the swash zone was surveyed at LLD+700cm in the Durban area, whilst at Ballito and Salt Rock the same swash levels were recorded at locations with a southerly aspect, adjacent to headlands. The erosion line for this storm was consistently located between the 4 and 5m contours above mean sea level, with the high water mark retreating by between 10-30m in a few hours as the nearshore sand was rapidly washed away. These extraordinary levels are consistent with the extreme intensity of the storm and the dramatic damage along the coast. “Roads were damaged at Margate, Uvongo, St Michael’s-on-Sea, Port Shepstone, Umkomaas, Durban, Umdloti, Ballito and Zinkwazi. The South Coast railway-line experienced severe damage at Mtwalume and Sezela. Private property along the coast was also damaged. The provisional repair bill exceeds one billion rand. (*Smith, Guastella, Bundy and Mather 2007*)”.



Potential Damage from Coastal Erosion

Coastal type and exposure influenced the severity of damage along the KZN coast. Sandy and rocky coastal sections generally withstood the storm's onslaught, but mixed coastlines of rock and sand, especially pocket beaches, were severely impacted. Many built structures that failed were located adjacent to, or upon rocky, headlands and within bays encompassed by rock shelves. Wave energy was focused in these areas, especially where over wash was not allowed to dissipate naturally.

There are lessons for the identification of areas along the coastline of the City of Cape Town which are vulnerable to the impacts from severe storms. Dunes must be high enough (at least 5m for the erosion line) and wide enough (room for a high water retreat of 30m) to afford protection from the sea. Once breached, infrastructure and services on land beyond the dunes is exposed to the risk of direct attack from the sea. A careful investigation of the land behind the sandy beaches of Table Bay and False Bay is indicated. Deep water channels leading into pocket beaches can be a focusing conduit for wave energy from destructive storms. An important lesson from the KZN storm is that buildings too close to the sea at the head of pocket beaches are at particular risk of severe damage. There are many exposed pocket beaches along the Atlantic coast of the Cape Peninsula. It should not be forgotten that the KZN storm was a cut-off low, leading to long wave surge from the east, a synoptic situation which also on occasion affects the western coastline of False Bay.

Scenario One

This is the **Present Day Very Worst Case Scenario** for the 300km coastline under the jurisdiction of the City of Cape Town. It results from the simultaneous occurrence of an extreme tide and an extreme storm, an event with a nominal return period of 500 years. Such an event has not occurred along the Cape coast in recent years but it did occur along the KZN coast on 19/20 March 2007. Measurements taken from the KZN extreme event have been incorporated into this Present Day Very Worst Case Scenario, particularly in respect of exposed and very exposed portions of the coastline. The erosion damage in KZN was spectacular, and similar damage should be anticipated along vulnerable sections of the Cape Town coast in such circumstances. The identification of these vulnerable sections of the Cape Town coast is an important output from this scenario.

The permissible resolution for sea levels in the GIS Inundation Model is 0.5m, and expected levels for scenarios should be rounded up from the levels reported earlier in the historic analysis. The maximum levels that should, therefore, be expected to be reached by the sea in this Present Day Very Worst Case Scenario are:

- LLD+2m in sheltered environments,
- LLD+4.5m in exposed environments, and
- LLD+6.5m in very exposed environments.

The levels reached in the exposed and very exposed environments along flat sandy beaches and into pocket beaches, are due to extreme swash heights associated with wave set up and run up in the surf zones from ~8m waves at the breakpoint. Even higher levels were measured at the limit of the swash zones in places where the greatest damage was caused along the KZN coast.

The inundation to be shown in the GIS reconstruction should identify those sections of the Cape Town coast that are most at risk in this Present Day Very Worst Case Scenario. Vulnerable infrastructure and services should be highlighted. Of particular interest will be where existing (dune) protection is eroded away in the storm and seawater is able to reach into unexpected areas of low-lying land. Because this scenario is possible (though unlikely) in the present day situation, it deserves to be carefully studied so that the extent of potential economic loss can be assessed.

SECOND STUDY

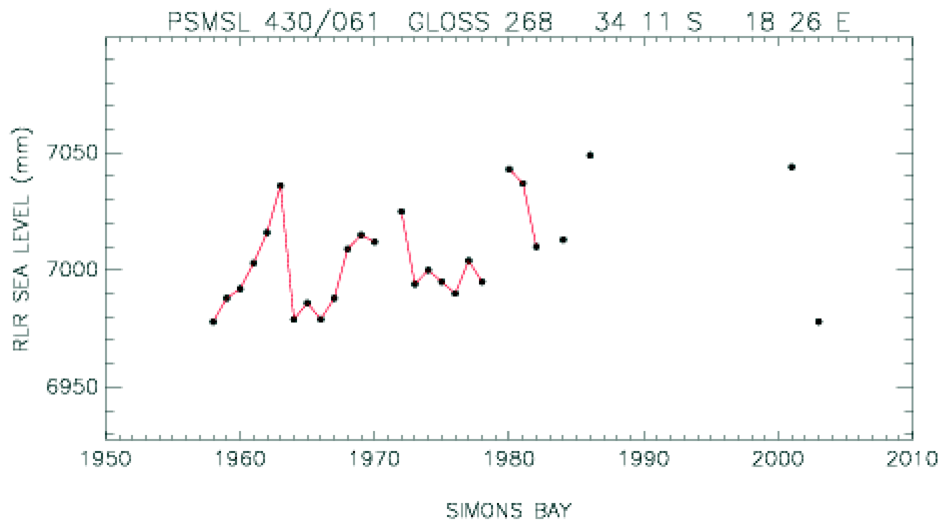
SEA LEVEL RISE PROJECTIONS IN THE NEAR FUTURE

ALONG THE COASTLINE OF THE CITY OF CAPE TOWN

Observations of sea level globally show a statistically significant sea level rise as part of human-induced climate change. At present, the rate of sea level rise is slow, but it does appear to be accelerating. This second study is intended to describe the situation along the coastline of the City of Cape Town, and to extrapolate from this situation so as to provide an estimate of the likely trends in the near future. The potential massive contribution to sea level rise from new climate change processes such as the melting of the polar ice sheets is the subject of the third study.

The primary effects of climate change in the coastal zone are the potential modifications due to sea level rise and storminess. The latest sea level rise predictions and their applicability to southern Africa are reviewed in *Theron 2007*, providing a useful context within which to place this study of sea level rise along the coastline of the City of Cape Town. Any analysis of sea level rise requires careful and consistent observations of sea level over several decades. These are not really available in South Africa (*Brundrit 1995*), nor in Africa as a whole (*Woodworth, Aman and Aarup 2007*).

A relatively long record of annual mean sea level is available for Simon's Bay from the Permanent Service for Mean Sea Level, which applies rigorous quality checks on such data. The PSMSL uses RSR sea level rather than LLD as its datum. At Simon's Bay, RSR is 6.846m below LLD, so that 7.000m RSR is 15.4cm above LLD.



It can be seen that there is reliable data only over a thirty year period from 1958 to 1986, but nothing in more recent years. Some important conclusions can be drawn from the reliable data. Annual mean sea level appears to shift between two distinct warmer and cooler climate states. Similar warmer and cooler states are found in annual sea surface temperature observations for the South Atlantic. Both climate states exhibit an upward trend in sea level of approximately 2mm per year, which is consistent with the accepted global rate of sea level rise over the same period. This means that more recent estimates of global sea level rise can be used as proxies for extending the rate of sea level rise into the period of unreliable data for Simon's Bay.

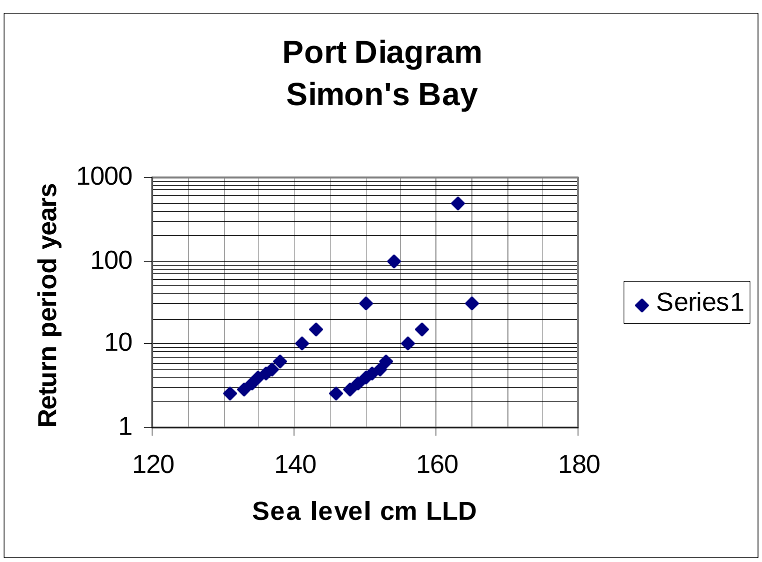
The Intergovernmental Panel on Climate Change in its Fourth Assessment Report has provided a Summary for Policy Makers of its 2007 Climate Change Synthesis Report. In discussing observed changes in climate and their effects, the IPCC reports as follows. "Rising sea level is consistent with warming. Global average sea level has risen since 1961 at an average rate of 1.8 [1.3 to 2.3] mm per year and since 1993 at 3.1 [2.4 to 3.8] mm per year”, and “Whether the faster rate for 1993 to 2003 reflects decadal variation or an increase in the longer term trend is uncertain”.

In its projections of future changes in climate over the 21st century, the IPCC draws on a set of models of sea level rise at 2090-2100 relative to 1980-1999, which exclude rapid dynamical changes in ice flow. This is an important reservation. The recently documented ice melting, both at sea and on the polar ice-caps, has led the IPCC to abandon its earlier projections. Now in its Synthesis Report of November 2007, it states that “because understanding of some important effects driving sea level rise is too limited, this report does not assess the likelihood, nor provide a best estimate or upper bound for (future) sea level rise”.

It would therefore appear to be prudent to restrict projections of sea level rise based on extrapolations of current trends to the next decade alone. Even there, the extrapolations would cover a wide range, depending on whether sea level rise reverts to its earlier rate, maintains its new rate, or continues to accelerate at a constant rate.

Decade	revert	steady	accelerate
1980-1989	1.8cm	1.8cm	1.8cm
1990-1999	3.1cm	3.1cm	3.1cm
2000-2009	1.8cm	3.1cm	4.4cm
2010-2019	1.8cm	3.1cm	5.7cm
accumulated	8.5cm	11.1cm	15.0cm

At the end of the next decade, the sea level to be expected is not a great change from present day circumstances. Thus there is little threat of additional inundation. What is different is how often any particular sea level can be expected. This can be seen by plotting additional points on the earlier Port Diagram for Simon's Bay. As well as the return periods based on the original observed annual maximum sea levels from 1960-1990, and the extrapolations for return periods of 100 and 500years, the new points increase each observed sea level by 15cm, whilst retaining their return period. This is the Port Diagram relevant to the present day and to the end of the next decade.



The present day extreme sea level of LLD+163cm with an expected return period of 500 years should be compared with the sea level of LLD+165cm expected to occur with a return period of only thirty years at the end of the next decade. While the observed maximum sea level of LLD+150cm from 1960-1990 is expected to occur with a return period of just four years at the end of the next decade. In the future, storms will cause more damage because they are built upon higher sea levels. Given that climate change is expected to increase the frequency of extreme storms, the situation could well become even more serious.

Scenario Two

This is the **Scenario at the End of the Next Decade** after the acceleration in sea level rise which is expected to add 15cm to base levels. Given the resolution of 0.5m in the GIS Inundation Model, the levels to be used in this Scenario Two and the details of the inundation to be expected are the same as in Scenario One!

- LLD+2m in sheltered environments,
- LLD+4.5m in exposed environments, and
- LLD+6.5m in very exposed environments.

Thus, every conclusion to be drawn from the impact of Scenario One on the infrastructure and services provided by the City of Cape Town is immediately relevant to this Scenario at the End of the Next Decade.

It is the circumstances of how often this Scenario Two is expected that are different. Rather than being a Very Worst Case Scenario with a return period of 500 years, Scenario Two is to be expected whenever an extreme storm occurs at the same time as any (fortnightly) spring high tide in the spring or autumn. With the further expectation that extreme storms will become more frequent under climate change, this Scenario at the End of the Next Decade is a realistic expectation rather than an unusual event for the end of the next decade.

All the effort made in understanding the impacts and vulnerabilities of present day Scenario One can then be used to illustrate what might be expected as the norm for Scenario Two at the end of the next decade, when extreme spring and autumn storms coincide with spring tides.

THIRD STUDY

SEA LEVEL RISE SCENARIOS ALONG THE COASTLINE OF THE CITY OF CAPE TOWN AFTER COLLAPSE OF THE POLAR ICE SHEETS

The timing of future sea level rise in the longer term is problematic. The Intergovernmental Panel for Climate Change has withdrawn any upper bound estimate to its forecasts of sea level rise over the 21st century. An alternative and preferable approach for the longer term future is to link sea level rise to the possible stabilization levels of greenhouse gases in the atmosphere and the accompanying global warming and polar ice melt. This is the approach which is recommended in the *Stern Review (2007),* and then followed in the *IPCC Synthesis Report (Nov 2007).*

The following linkages of climate change are expected from the sets of climate models which are used in the *Stern Review (2007).* It should be noted that the present level of carbon dioxide equivalent is at 380ppm, and rising. Any stabilization level will require urgent global action on constraining the input of greenhouse gases into the atmosphere.

Scenario A.

450ppm carbon dioxide equivalent stabilization level

2 degree Celsius temperature rise

1m sea level rise from thermal expansion only

Rising intensity and frequency of storms

Onset of irreversible melting of the Greenland Ice Sheet

Initiation of further sea level rise as the melting progresses

Scenario B.

550ppm carbon dioxide equivalent stabilization level

3 degree Celsius temperature rise

1.5m sea level rise from thermal expansion only

Significant contribution to sea level rise from the Greenland Ice Sheet

Increasing risk of collapse of the West Antarctic Ice Sheet

Sea level rise of a few metres

Scenario C.

750ppm carbon dioxide equivalent stabilization level

4 degree Celsius temperature rise

2m sea level rise from thermal expansion only

Yet more storminess

Onset of collapse of the West Antarctic Ice Sheet

Eventual sea level rise of over ten metres

These linkages are illustrated with median levels of each quantity; there are considerable spreads about these median levels. Lower stabilization levels are unlikely. It is important to recognize that no time scales are provided for these scenarios. However, the gradual progression of climate change through the stabilization levels, global warming and polar ice melt will provide better estimates of the timing and extent of global sea level rise.

The *IPPC Synthesis Report (2007)* follows the *Stern Review(2007)* and considers projections of future climate change over and beyond the 21st century. Rapid sea level rise on century time scales cannot be excluded. Net ice loss will set in with a global average warming in excess of 2 degrees Celsius, marking the onset of an accelerating ice melt contribution to sea level rise. The complete elimination of the Greenland Ice Sheet will eventually lead to a contribution to sea level rise of 7m. These temperatures correspond to those of the last inter-glacial of 125000 years ago, when sea level was 4 to 6 m higher than present levels. Around the Cape Peninsula the sea level at this time is reasonably well marked as the 18 foot wave cut platform. It should be noted that this feature has been utilized for road and rail communication, eg the railway line from Muizenberg to Simon’s Town!

The prime effect of the rapid sea level rise over the longer term future is the permanent inundation of low lying coastal areas, rather than the intermittent effect of storm damage. As sea level rise continues, it will lead to the wholesale disruption of services along the coast. In the GIS model, these scenarios extracted from the *Stern Review (2007)* can be illustrated with a mean sea level rising from LLD in steps of 1m up to LLD+12m.

Scenario Three

When wholesale melting of the Greenland and West Antarctica Ice Sheets begins to contribute to sea level rise, the anticipated levels will be greatly in excess of earlier levels. This leads to the **Polar Ice Sheet Melt Scenario.** There is much uncertainty about the extent and the timing of the melting of the polar ice sheets and their eventual contribution to sea level rise and coastal inundation. Consequently, this Scenario Three is fundamentally different from the earlier scenarios. The focus should be on Mean Sea Level and the changes to be expected from the ice melt alone, so as to provide an every day scenario for these circumstances. It will map the location of the new coastline. Tides and storms can be added later, if need be, to illustrate the variability to be expected on a day by day basis.

Because storms are excluded, there is now no difference between sheltered and exposed sections of coast; all experience the same sea level. In the GIS model, only one colour will be needed to illustrate the inundation from sea level rise affecting the entire coast. I suggest that this be shown as LLD, LLD+2m, LLD+4m, LLD+6m etc moving steadily upwards in steps of 2m to (say) LLD+12m. (Perhaps the levels should be taken up to when the Cape Peninsula becomes an island!)

In this Polar Ice Sheet Melt Scenario, the important information that will come from the GIS inundation model will be the **order** in which different land areas are overwhelmed in the inexorable rise in sea level. Emphasis can then be placed on separate categories of infrastructure and services, such as loss of industrial areas, residential areas and disruption of the transport networks. The information on the order in which disruption will occur will aid in preparation for adaptive planning for the very worst consequences of sea level rise on the City of Cape Town. Remember that there is great uncertainty on the timing of such a long lead time scenario; this is a scenario not a prediction.

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THE THREE SCENARIOS

AS INPUT TO THE GIS INUNDATION MODEL

Three Scenarios are presented, one from each of the three studies.

Scenario One.

This is the **Present Day Very Worst Case Scenario** for the 300km coastline under the jurisdiction of the City of Cape Town. It results from the simultaneous occurrence of an extreme tide and an extreme storm, an event with a nominal return period of 500 years. Such an event has not occurred along the Cape coast in recent years but it did occur along the KZN coast on 19/20 March 2007. Measurements taken from the KZN extreme event have been incorporated into this Present Day Very Worst Case Scenario, particularly in respect of exposed and very exposed portions of the coastline. The erosion damage in KZN was spectacular, and similar damage should be anticipated along vulnerable sections of the Cape Town coast in such circumstances. The identification of these vulnerable sections of the Cape Town coast is an important output from this scenario.

The scenario should use three colours to identify inundation of three sections of the coastline:

1. Sheltered and hard (rocky or armoured) sections of the coast.

2. Exposed sandy beach (and low-lying) sections of the coast, subject to erosion from the storm.

3. Very exposed sandy beach (and low-lying) sections of the coast, subject to extreme erosion.

The maximum levels that should be expected to be reached by the sea in this Present Day Very Worst Case Scenario in the environments as above are:

LLD+2m in sheltered environments,

LLD+4.5m in exposed environments, and

LLD+6.5m in very exposed environments.

The levels reached in the exposed and very exposed environments along flat sandy beaches are due to extreme swash heights associated with wave set up and run up in the surf zones from ~8m waves at the breakpoint. Even higher levels were measured at the limit of the swash zones in places where the greatest damage was caused along the KZN coast.

The inundation shown in the GIS reconstruction should identify those sections of the Cape Town coast that are most at risk in this Present Day Very Worst Case Scenario. Vulnerable infrastructure and services should be highlighted. Of particular interest will be where existing (dune) protection is eroded away in the storm and seawater is able to reach into unexpected areas of low-lying land. Because this scenario is possible (though unlikely) in the present day situation, it deserves to be carefully studied so that the extent of potential economic loss can be assessed.

Scenario Two

This is the **Scenario at the End of the Next Decade** after the acceleration in sea level rise which is expected to add 50cm to base levels. The levels to be used in this Scenario Two and the details of the inundation to be expected are the same as in Scenario

One! Thus, every conclusion to be drawn from the impact of Scenario One on the infrastructure and services provided by the City of Cape Town is immediately relevant to this Scenario at the End of the Next Decade.

It is the circumstances of how often this Scenario Two is expected that are different. Rather than being a Very Worst Case Scenario with a return period of 500 years, Scenario Two is to be expected whenever an extreme storm occurs at the same time as any (fortnightly) spring high tide in the spring or autumn. With the expectation that extreme storms will become more frequent, this Scenario at the End of the Next Decade is a realistic rather than an unusual event for the end of the next decade.

All the effort made in understanding the impacts and vulnerabilities of Scenario One can then be used to illustrate what might be expected as the norm for big spring and autumn storms at the end of the next decade in Scenario Two.

Scenario Three

When wholesale melting of the Greenland and West Antarctica Ice Sheets begins to contribute to sea level rise, the anticipated levels will be greatly in excess of earlier levels. This leads to the **Polar Ice Sheet Melt Scenario.** There is much uncertainty about the extent and the timing of the melting of the polar ice sheets and their eventual contribution to sea level rise and coastal inundation. Consequently, this Scenario Three is fundamentally different from the earlier scenarios. The focus should be on Mean Sea Level and the changes to be expected from the ice melt alone, so as to provide an every day scenario for these circumstances. It will map the location of the new coastline. Tides and storms can be added later, if need be, to illustrate the variability to be expected on a day by day basis.

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