

Sea Level Activities and Changes on the Islands of the Western Indian Ocean

Sachooda Ragoonaden

30 Antelme Avenue, Quatre Bornes, Mauritius

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Abstract—During the Tropical Ocean Global Atmosphere (TOGA) 10- year programme (1985-1994), a sea-level study network was established in the Western Indian Ocean (WIO) to monitor sea-level variations. Most of these stations together with additional stations maintained by countries outside the region now form part of the Global Sea Level Observing System (GLOSS). The monthly research quality dataset for 13 island stations in the WIO between 06°N and 46°S and between the African coast and 80°E from the Joint Archive for Sea Level, located at the University of Hawaii, was used for the study. Using linear regression and 12-month moving average statistical methods to analyse the data, some useful results were obtained in spite of the short duration of the time series. It was noted that eight out of the 13 stations showed a rising trend and four a falling trend, a tendency illustrated also by TOPEX/Poseidon satellite data (1993-2000). This provides some evidence that there is no clear indication of any great acceleration in sea level rise in the region. The GLOSS network should be maintained and expanded with additional stations of regional importance to ensure a long term series of sea level data to monitor sea level changes. This is a useful input in decision making for sustainable development of coastal resources as well as providing a vital tool to detect tsunami signals for early warning purposes.

INTRODUCTION

The reality of global warming is now well established and the “balance of evidence suggests that there is a discernible human influence on global climate” (IPCC, 1996). Globally the last ten years have been the warmest decade recorded since the 1850’s with the highest average temperature observed in 1998 (+0.54°C above the mean 1961-1990) followed by 2003 (+0.51°C), 2002 (+0.47°C) and 2004 (+0.44°C). Moreover, October 2004 was the warmest month ever observed since 1861 (WMO press release, 2005). The Western Indian Ocean also witnessed some abnormally high temperatures during the last decade and 2003 was the warmest year observed in Mauritius since 1930 (Mauritius Meteorological Service report, 2003).

One of the most likely consequences of global warming is an Accelerated Sea Level Rise (ASLR) due mainly to oceanic thermal expansion and melting of glaciers, Greenland and Antarctic ice sheets. Comparison of the rate of SLR over the last 100 years (1 to 2 mm/yr) with the geological rate over the last two millennia indicates a relatively recent acceleration in the rate of sea level rise in the last century (IPCC, 2001a). Moreover, precise radar altimetry observations from TOPEX/Poseidon have suggested a rate of rise nearer to 3 mm/yr during the 1990s (Cabanès *et al.*, 2001; Nerem and Mitchum, 2002; Leuliette *et al.*, 2004), a value greater than the mean rate over much of the 20th century (IPCC, 2001a). Holgate and Woodworth (2004) have found from analysis and comparison of tide gauge and satellite data that

the rate of sea level rise was anomalously large in the 1990's. They also concluded that sea level rose faster at the coast than the global average over the last decade. This has significant implication for coastal populations and for planners of coastal development works.

Sea level rise poses by far the greatest threat to Small Island Developing States (SIDS) relative to other countries. The prospective of ASLR in this century makes beach erosion more likely (Nicholls, 1998). It has been estimated that shoreline recession is in the range of 100 to 200 times the sea level rise scenario (Brunn, 1962). Using a simple version of the Brunn rule and taking into account a projected mean rise of sea level of 0.49 cm (IPCC, 2001a), this implies that 50m to 100m of beaches will be eroded by the end of the century. This has given rise to growing concern among SIDS governments. Since the historical statements of the President of Maldives at the United Nations General Assembly and during the Small Island States Conference on sea level held in Malé, Maldives in November 1989, many atolls mostly in the South Pacific have been abandoned due to frequent inundations and their populations relocated. In Maldives, in order to protect the capital Malé from frequent flooding, a breakwater has been constructed around the capital costing around US\$30 million. Some of its islands have been abandoned. The December 2004 tsunami is another vivid illustration of the vulnerabilities of SIDS in the Indian Ocean region to extreme natural events.

ISLANDS OF THE WESTERN INDIAN OCEAN

The Western Indian Ocean is defined here as the region between 06°N and 46°S latitude and between the African Coast and 80°E. It includes the islands of Maldives, Seychelles, Gan, Diego-Garcia, Mauritius, Kerguelen, Crozet, St Paul, Mayotte, Zanzibar, Rodrigues, Reunion and Madagascar, where sea level data are available on an almost continuous basis since the 1980's. Reunion, Kerguelen, Crozet and St. Paul are islands that have tide gauges operated by French groups.

These countries are geographically and demographically diverse. They may comprise a

single island (for example Mauritius, Kerguelen), a few islands (Gan, Diego-Garcia) or numerous islands - Seychelles (115) and the Maldives (2000). Some are of volcanic origin and mountainous with fringing reefs around them and shallow lagoons (Mauritius, Seychelles). Others are atolls and low lying islands barely a few metres above mean sea level (Maldives, Diego-Garcia and Gan), while Madagascar can be considered as a big island. The majority of SIDS in the region are poor countries and Climate Change (CC) and SLR will worsen their socio-economic situation.

PAST STUDIES ON SEA LEVEL CHANGES

Studies on past sea level changes are limited in the WIO due mainly to lack of long series of sea level data. The only island with a long history of sea level record is Mauritius. Early sea level measurements were initiated in 1929 but only for a limited period. The tide gauge station was established mainly to serve navigation activities and ample information on the tidal regime was obtained after a few years of observation. Some measurements were also made at the end of 1960's by HMS Owen to calculate the mean sea level and establish a datum for Mauritius. Based on tide gauge station data that is long enough to be useful for estimating changes in the relative sea level, Emery and Aubrey (1989) calculated a relative sea-level rise of approximately 3 mm/yr. Another study (Ragoonaden, 1997) indicated that since 1965 sea level rose about 1.2 mm/yr, which is comparable to the global sea level rise during the last century.

Analysis of sea level data at Reunion Island (Piton, 1998) has given rise to some interesting observations. It was noted that sea level was abnormally low in September 1992 at Reunion and was as much as 15 to 20 cm below normal during some days. In Mauritius, the monthly mean sea level for August-September 1992 was about 19 cm below average for the same period in 1991. Large-scale circulation anomalies in the Indian Ocean could have given rise to this low water level as the wind stress over the Indian Ocean in September 1992 was much stronger than in September 1991. This could have caused an intensification of the ocean circulation over the whole Indian Ocean with

more intense mixing leading to enhanced upwelling. Sea temperature in September 1992 was about 1°C below that of September 1991. It is to be noted that a severe drought occurred in Reunion from September to November 1992.

CURRENT SEA LEVEL NETWORK IN THE INDIAN OCEAN

A well-established sea level network was initiated during the 10-year Tropical Ocean Global Atmosphere (TOGA) programme (1985-1994), a component of the World Climate Research Programme (WCRP) of the World Meteorological Organization (WMO), Intergovernmental

Oceanographic Commission (IOC) of UNESCO and International Council for Science (ICSU). The TOGA Sea Level Centre (SLC) was set up at the University of Hawaii for acquiring, processing and archiving sea level data from the tropics. Additional sea level stations were established during the IOC/WMO International World Ocean Circulation Experiment (WOCE) programme, another component of WCRP (Woodworth *et al.*, 2002). Most of the stations now form part of the IOC/WMO Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) Global Sea Level Observing System (GLOSS) programme.

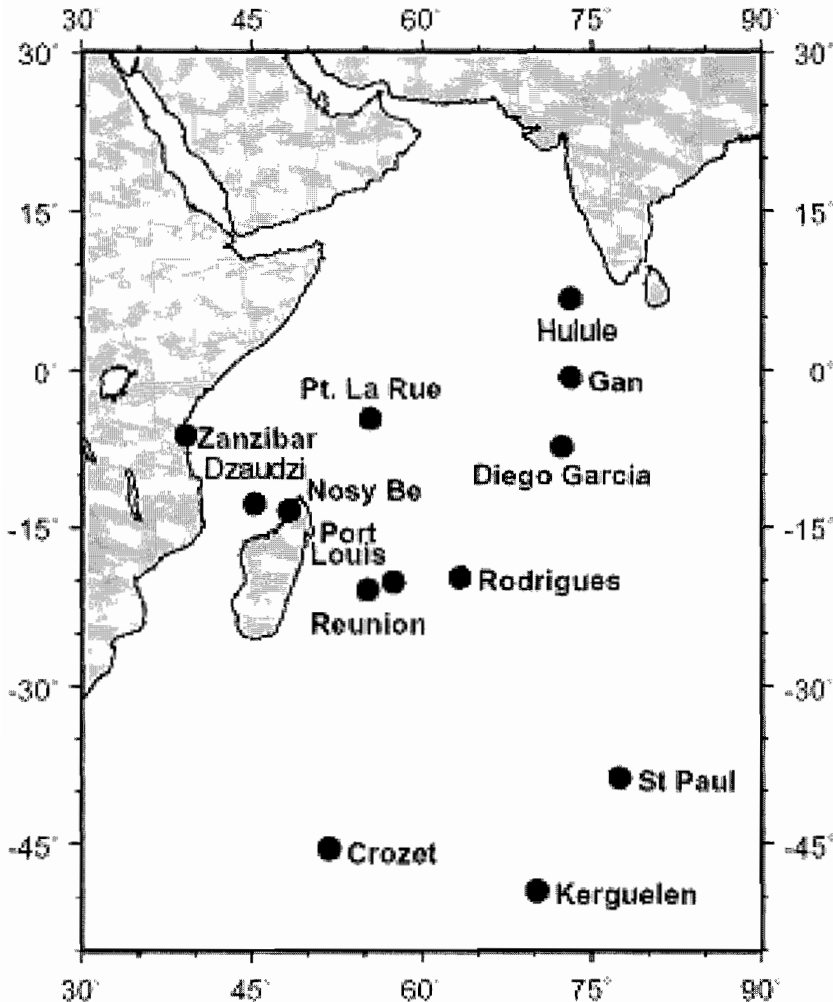


Fig. 1. Sea Level Stations Location

Most of the sea level stations in the WIO, the data of which are being used in the study, were established within the framework of TOGA and WOCE from 1986 and were of the conventional float type. Hourly and daily sea level data for the network are submitted on a regular basis to the TOGA SLC and monthly data to the Permanent Service for Mean Sea Level (PSMSL).

A proposal for the development of a regional sea level network in the WIO within GLOSS has been formulated to address regional sea level variations (IOC, 1991). The establishment of fifteen new stations in addition to the 17 specified GLOSS stations is planned along the eastern coast of Africa. For the island countries, a few stations have been proposed besides the GLOSS stations - Farquhar (Seychelles), Moroni (Comoros), Tulear and Majunga (Madagascar).

DATA FOR THE STUDY AND METHODOLOGY

The monthly Research Quality Data Set (RDQS) of the TOGA SLC was used for the study. It was retrieved from the website of the Joint Archive for Sea Level (JASL), a collaboration between the University of Hawaii Sea Level Centre (UHSLC) and the World Data Centre - A for oceanography

(<http://ilikai.soest.hawaii.edu/UHSLC/jaslanrep.html>).

The JASL receives hourly data from regional and national sea level networks. The data are inspected, quality controlled, assessed and well documented. They are, hence, scientifically valid and quality assured. Information on the stations and data is given in Table 1. The GLOSS/CLIVAR "fast mode sea level data" is also available via the above website partly to provide information to calibrate satellite altimeter data.

The monthly values of sea level for each station using a statistical software package were plotted and lines of best-fit linear regression and 12 month moving average values were then superimposed on the plots.

RESULTS

In spite of the limited duration of the sea level record, some interesting findings have emerged. It is seen that the average sea level varies from month to month. The inter-annual changes are also quite significant. The sea level variation at the various sites exhibit different rates and directions of change with considerable variability in trend from region to region. Over the period under study, the tide gauge records provide a regional average

Table 1. Metadata on station network in WIO

Station	Position	Responsible Country	Period of Scientific research Data	Period of Fast Mode data
1. Diego-Garcia	07 29 S 072 23 E	United Kingdom	1988-2000	1998-on
2. Dzauzi	09 30 S 043 30 E	Mayotte	1985-1995	-
3. Gan	00 41N 073 09 E	Maldives	1987-2001	1987-on
4. Crozet	046 25 S 051 52 E	France	1995-2000	1995-on
5. Kerguelen	049 20 S 070 13 E	France	1993-1998	1993-on
6. Hulule	06 46 N 073 10 E	Maldives	1989-2003	-
7. Nosy-be	013 24 S 048 18 E	Madagascar	1987-1998	-
8. Pointe-La-Rue	04 40 S 055 31 E	Seychelles	1993-2004	1993-on
9. Port-Louis	020 09 S 057 40 E	Mauritius	1986-2003	1986-on
10. Reunion	019 30 S 056 30 E	France	1982-1986	-
11. Rodrigues	019 40 S 063 25 E	Mauritius	1986-2003	1986-on
12. St-Paul	038 42 S 077 32 E	France	1994-2001	-
13. Zanzibar	06 09 S 039 11 E	Tanzania	1984-2004	-

rate of +2.7 mm/year with a range of -3.6 mm/yr to +12.4 mm/yr. (Table 2)

Rising Trends

Eight out of the 13 stations show a rising trend with various rates of increase. This observation is illustrated in Fig 2 (a) to (h)). St Paul and Kerguelen

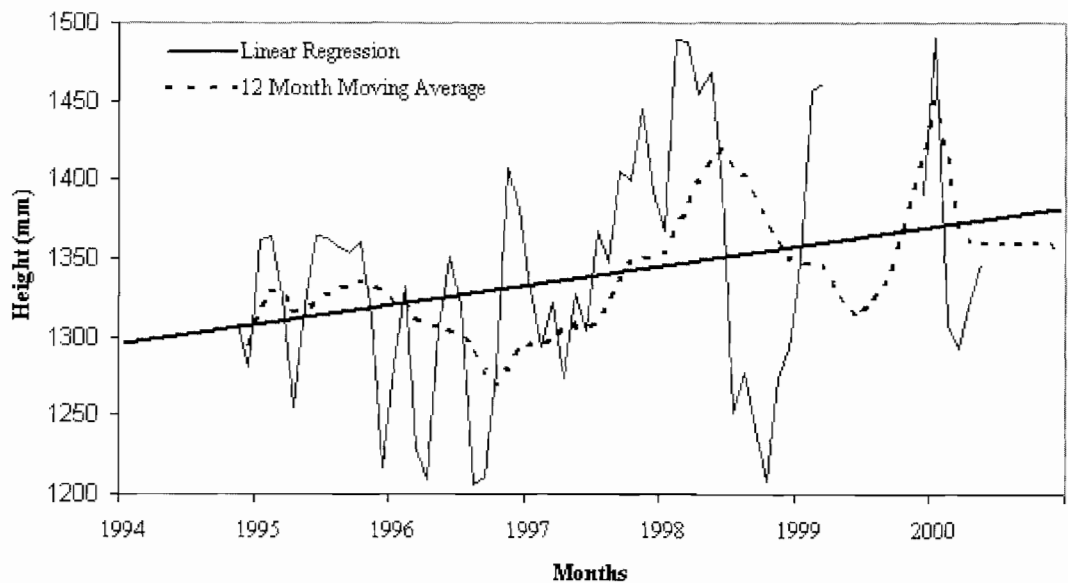
show very high rates of increase of the order of 12 mm/yr whereas at Dzauzi (Mayotte) only a slight rise was noted.

Falling Trend

Four stations show falling trend as illustrated in Fig 2 (a)-(d) with Zanzibar, east of Tanzania, giving

Table 2. Sea Level trend at the Island Stations

Stations	Trend	Annual range (cm)	Average Changes (mm/yr)
St Paul	Marked rise	19.4	+12.44
Kerguelen	Marked rise	11.3	+11.78
Gan	Significant rise	13.3	+ 4.68
Diego Garcia	Significant rise	18.1	+4.35
Nosy be	Significant rise	14.7	+3.31
Pointe La Rue	Rise	19.9	+1.69
Hulule	Rise	12.1	+1.29
Dzauzi	Slow rise	20.7	+0.40
Reunion	Slow fall	25.9	-0.10
Port-Louis	Slow fall	24.3	-0.10
Rodrigues	Fall	24.6	-0.32
Zanzibar	Significant fall	9.3	-3.64
Crozet	No comments	-	No comments



Note: Height in mm is based on an arbitrary datum

Fig. 2a. Time series of monthly mean sea level at St Paul, France

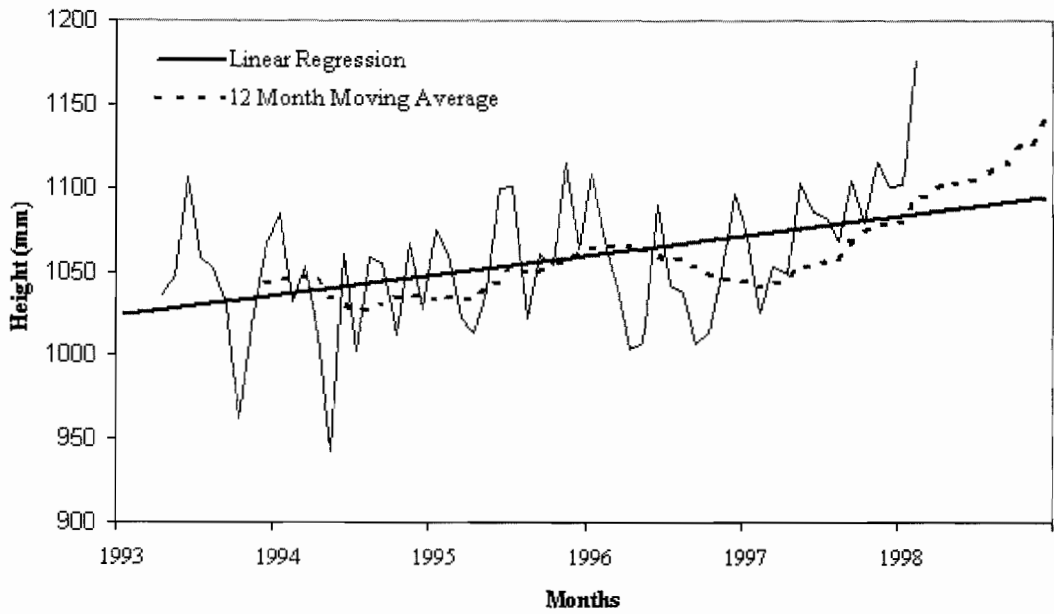


Fig. 2b. Time series of monthly mean sea level at Kerguelen, France

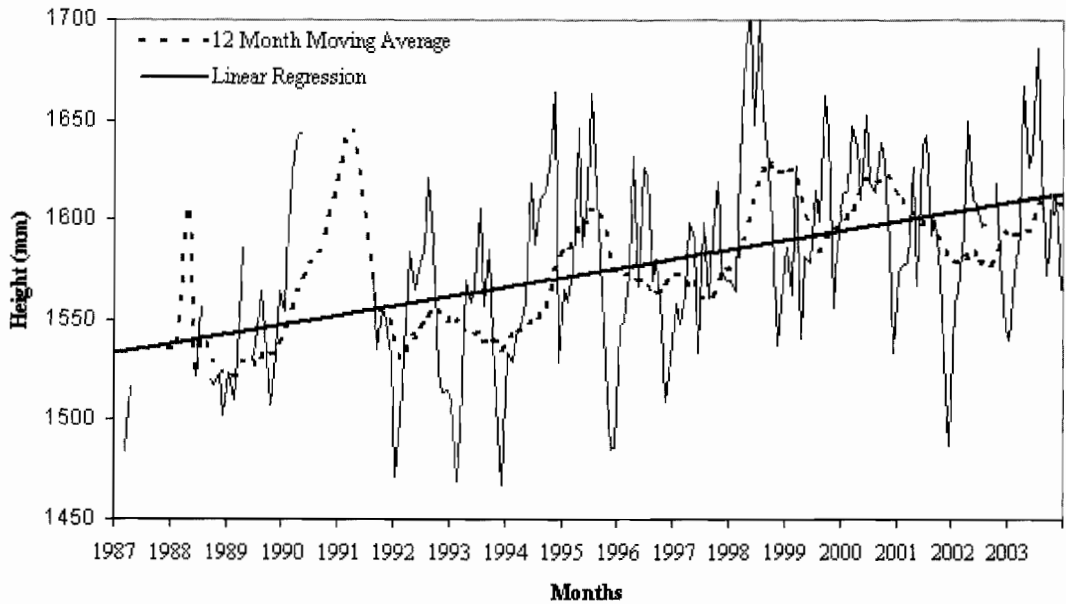


Fig. 2c. Time series of monthly mean sea level at Gan, Republic of Maldives

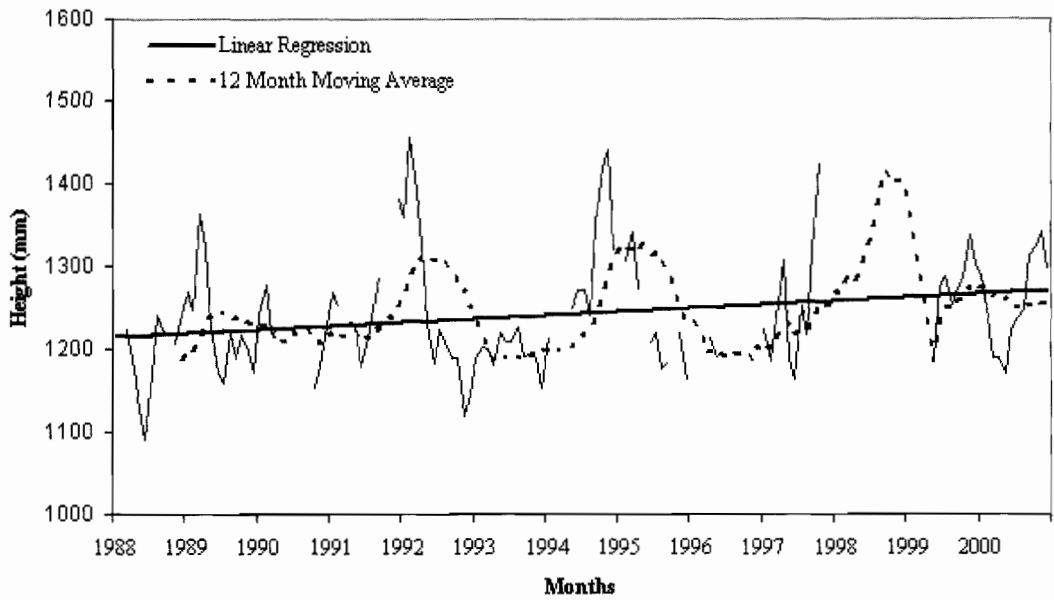


Fig. 2d. Time series of monthly mean sea level at Diego Garcia, United Kingdom

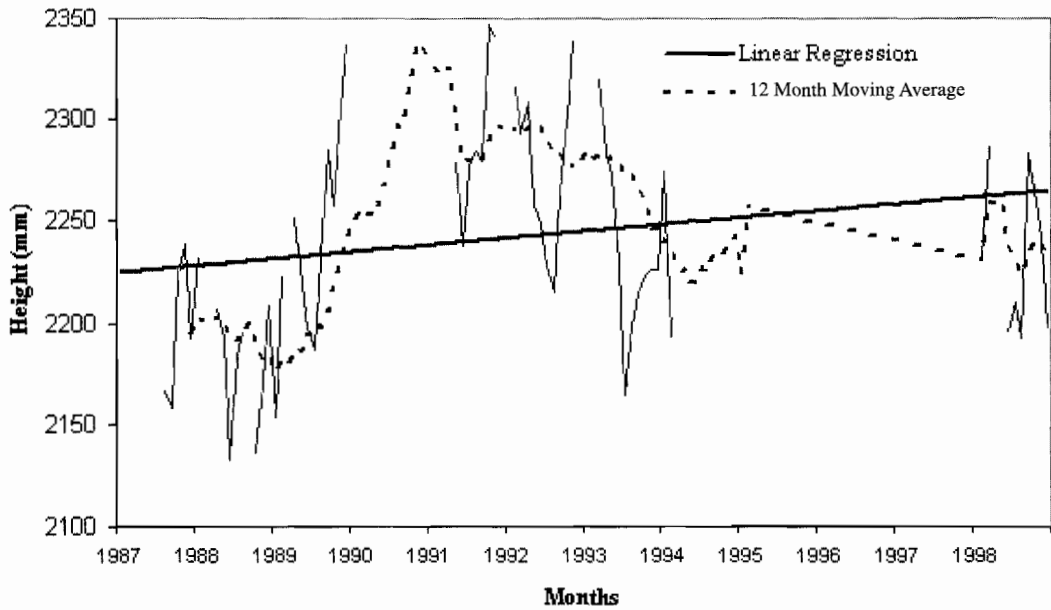


Fig. 2a. Time series of monthly mean sea level at Nosy Be, Madagascar

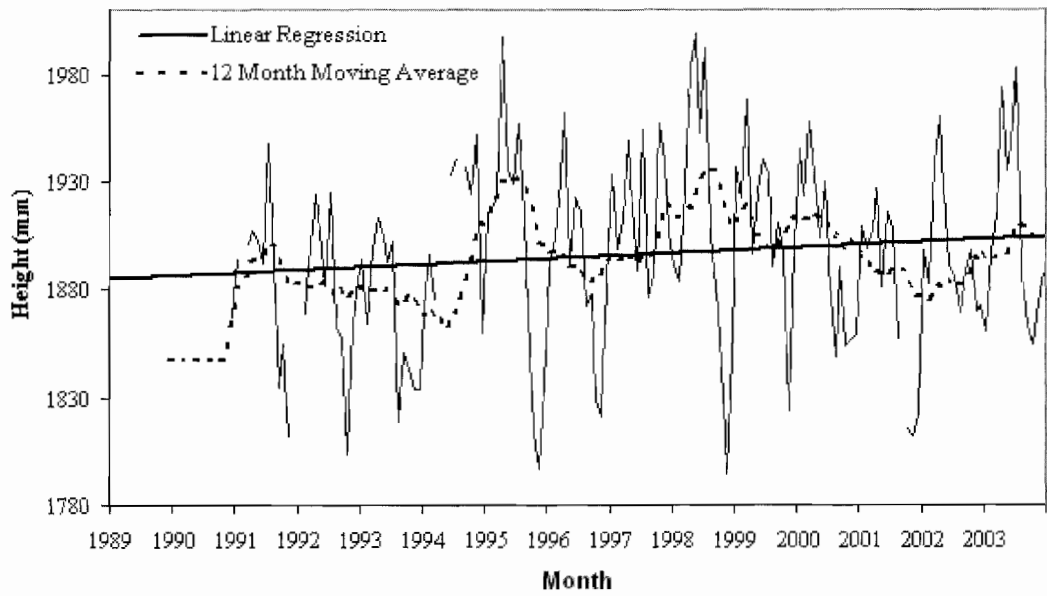


Fig. 2f. Time series of monthly mean sea level at Hulule, Republic of Maldives

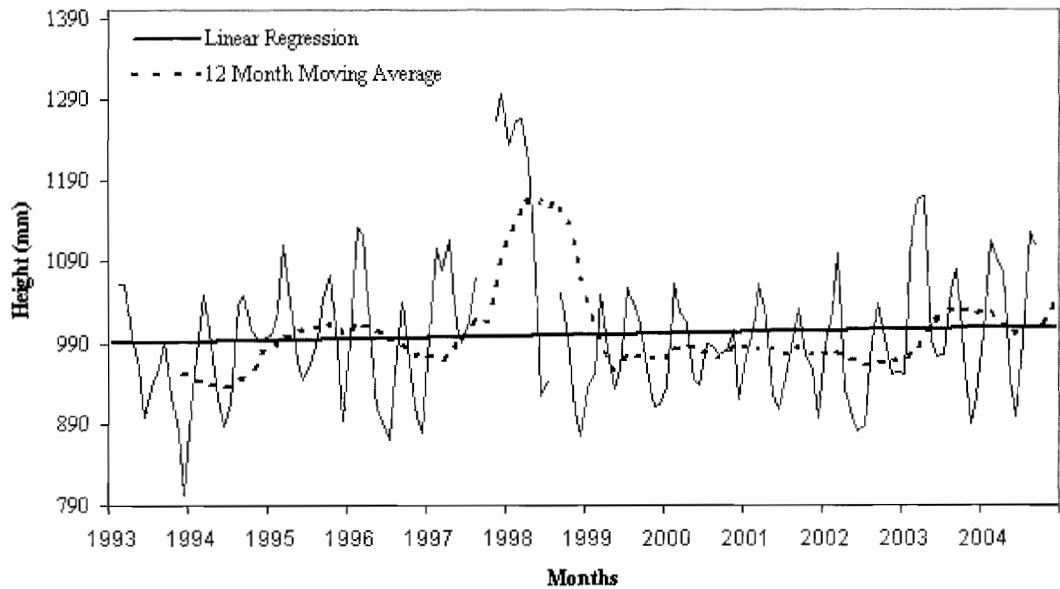


Fig. 2g. Time series of monthly mean sea level at Pointe La Rue, Seychelles

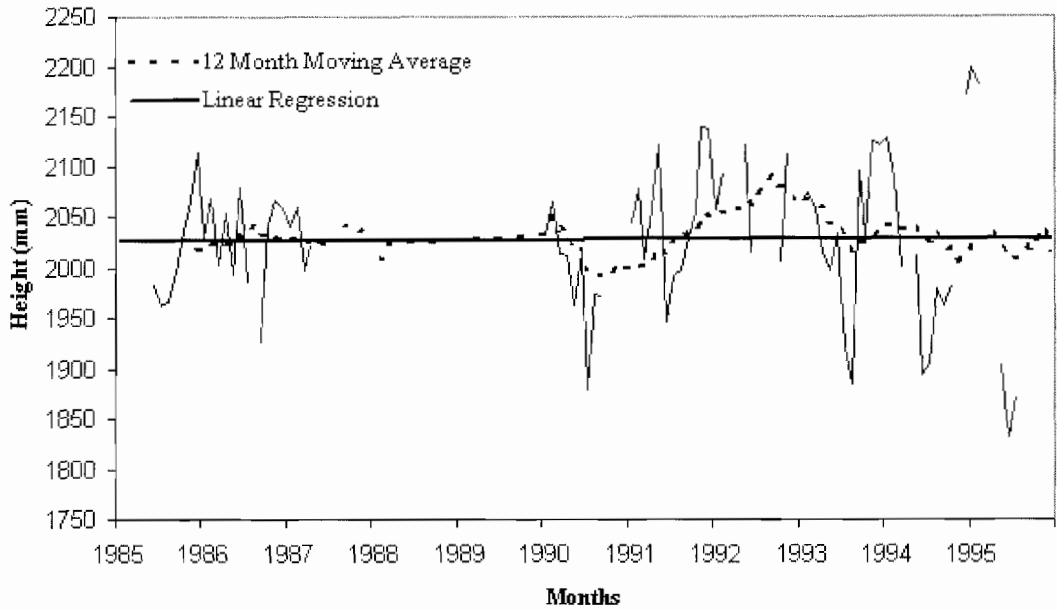


Fig. 2h. Time series of monthly mean sea level at Dzauzi, Comoros

the strongest signal in the region (-3.6 mm/yr). The Mascarene Islands (Mauritius, Rodrigues and Reunion) also show a small falling trend.

Ambiguous Case

The Crozet time series has been included in order to provide some indication that an additional sea

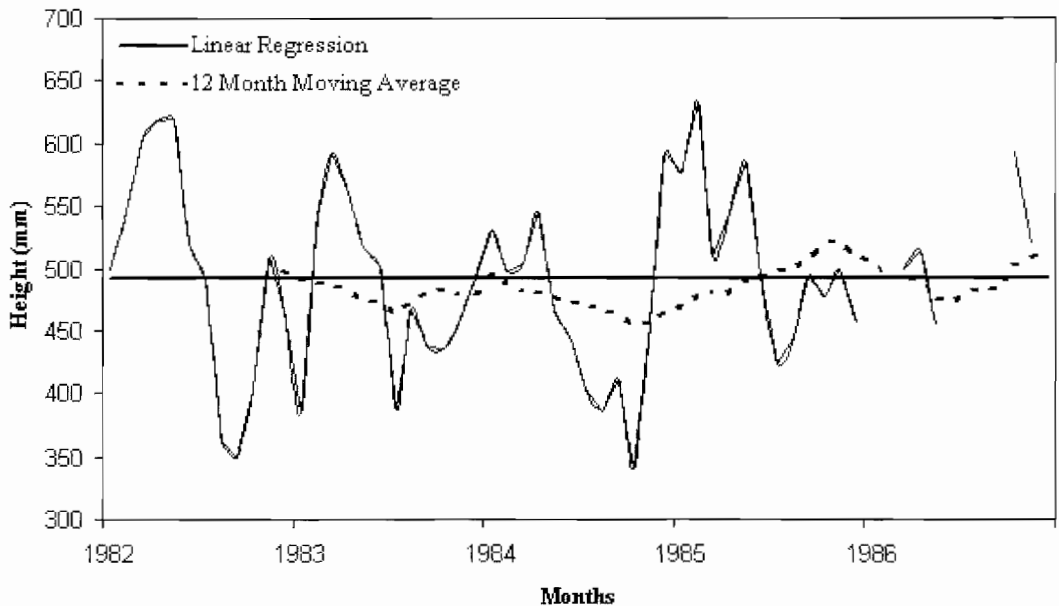


Fig. 3a. Time series of monthly mean sea level at Reunion, France

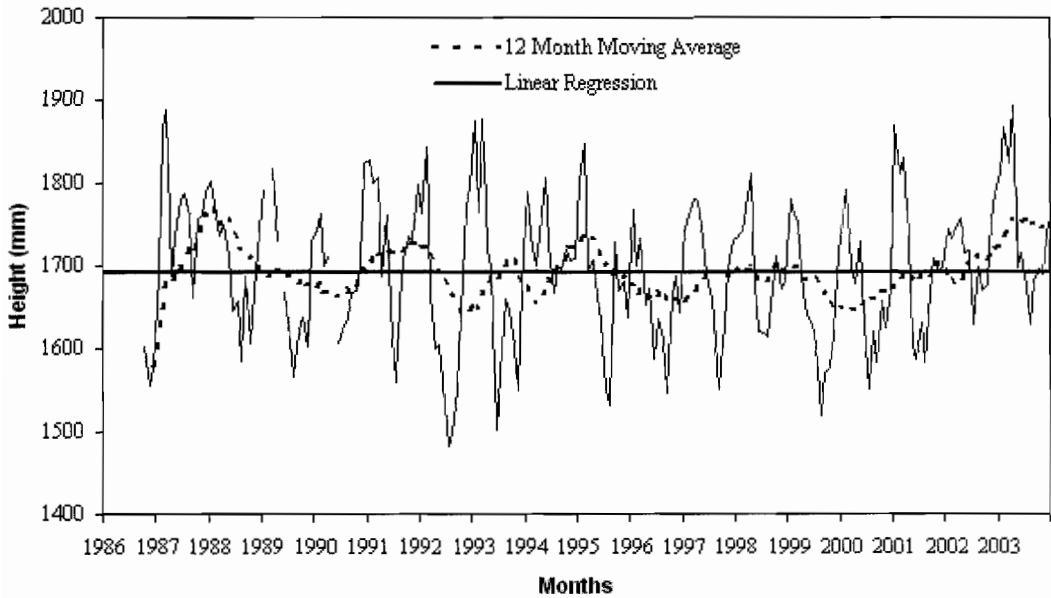


Fig. 3b. Time series of monthly mean sea level at Port Louis, Republic of Mauritius

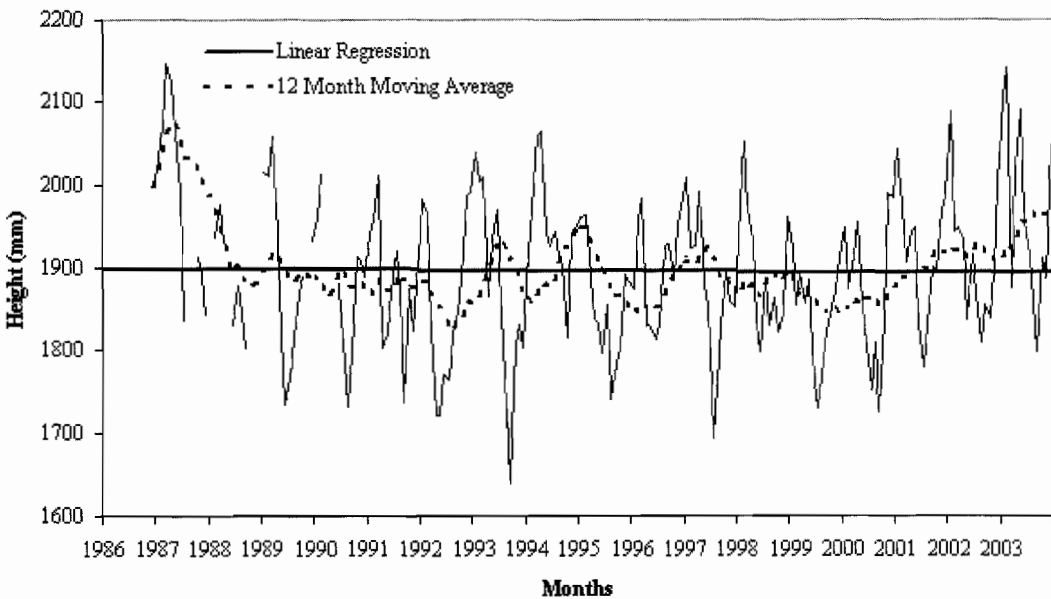


Fig. 3c. Time series of monthly mean sea level at Rodrigues, Republic of Mauritius

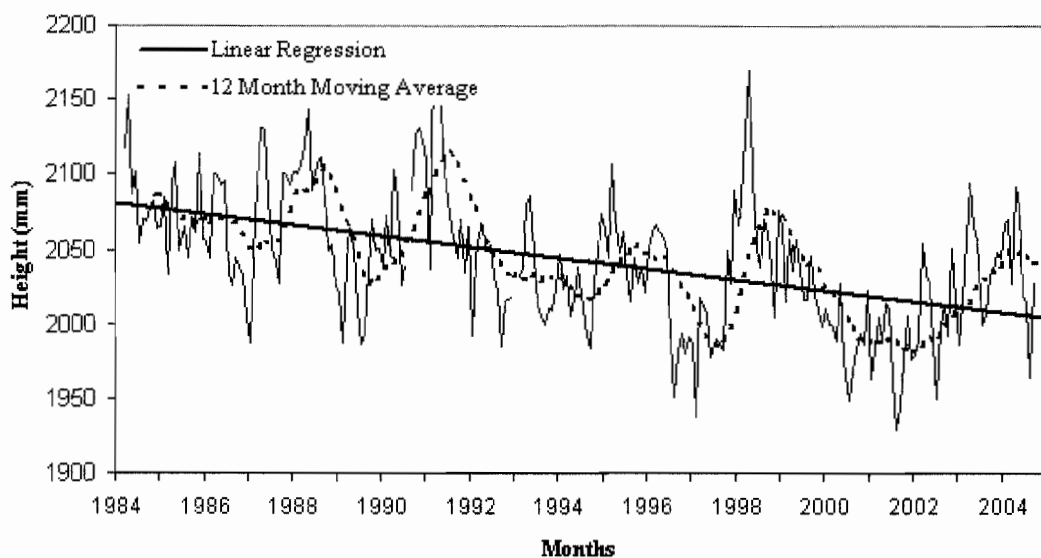


Fig. 3d. Time series of monthly mean sea level at Zanzibar, Tanzania

level station is in operation in the high latitudes of the South Indian Ocean for future studies. The abrupt change in the time series between the 2000 and 2001 (Fig.4) is clearly an instrumental datum

shift. Moreover, the tide gauge has proved problematic since its installation. It is located on probably the most environmentally hostile islands of this region and the site is very exposed to swell and waves (Testut *et al.*, 2006)

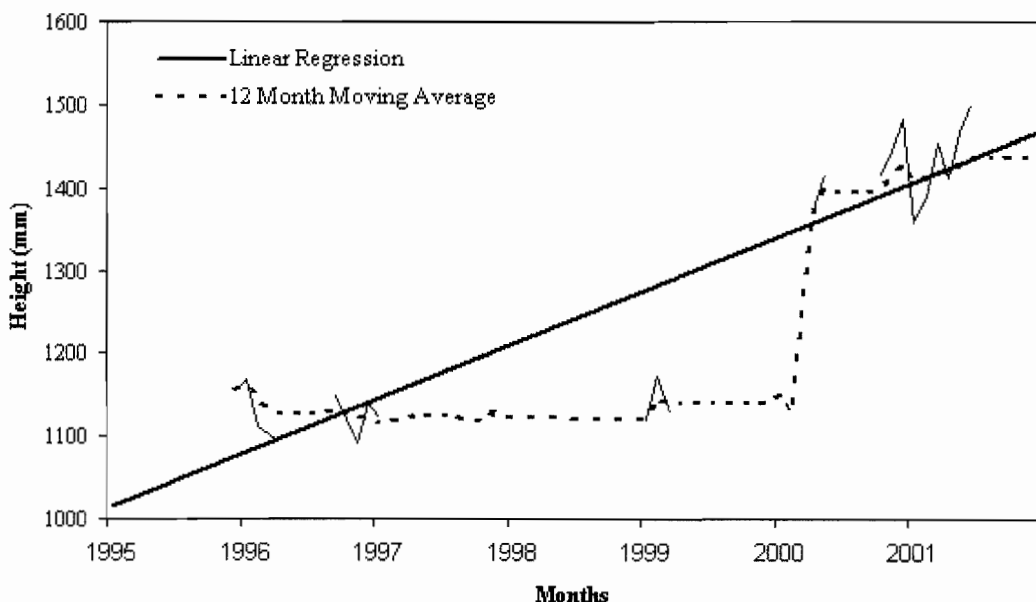


Fig. 4. Time series of monthly mean sea level at Crozet, France

DISCUSSION

It is usually considered that at least 20 years of data are required to identify trends (e.g. Pugh, 1987). On the other hand, the IPCC (2001a) recommends 50 years of continuous record in order to make any statement on issues related to climate change. In the WIO, no station has this length of record. Some stations have, nevertheless, more than 15 years of record for analysis to derive some meaningful interim output. The Caribbean and Pacific Ocean Islands also have no long term data series to determine with confidence a sea level trend. On the basis of available data, for some islands in the South Pacific Ocean (Gillie, 1997), it has been found that the relative sea level changes vary between +6.8 mm/yr (Papeete, French Polynesia) to -10.2 mm/yr (Rabaul, Papua New Guinea). The wide difference has been attributed to tectonic regimes though decadal variability of the ocean could provide another explanation. Similarly, some of the islands of the WIO are geologically quite young and still dynamic. The different tectonic regime including uplift or sinking in the region could explain why sea level changes differ so significantly from site to site.

Global sea level based on TOPEX/Poseidon satellite altimetry data is now routinely available (e.g. Holgate and Woodworth, 2004). It is noted from TOPEX/Poseidon satellite altimetry-derived map (Leuliette *et al.*, 2004, Figure 5) that since the 1990's the average sea level has been falling most significantly to the east of Madagascar in the regions of Mauritius and Rodrigues as well as east of Tanzania (dark blue region).

It is interesting to observe that the analysis of monthly in-situ tide gauge data for the three stations of the Mascarene Islands, namely Mauritius, Rodrigues, and Reunion give the same trend. Similarly, for most of the other stations, their trends coincide with the tendency as observed from the satellite data.

It can be argued thus that on the analysis of available data, there is no strong evidence that a major sea level rise has occurred recently in the WIO. In its Third Assessment report, the IPCC (IPCC, 2001a) too has concluded, inter alia, that there has been no significant acceleration in the rate of SLR during the 20th century. However, the rate of two to four times that of the 20th century is projected for the 21st century (IPCC, 2001a). This

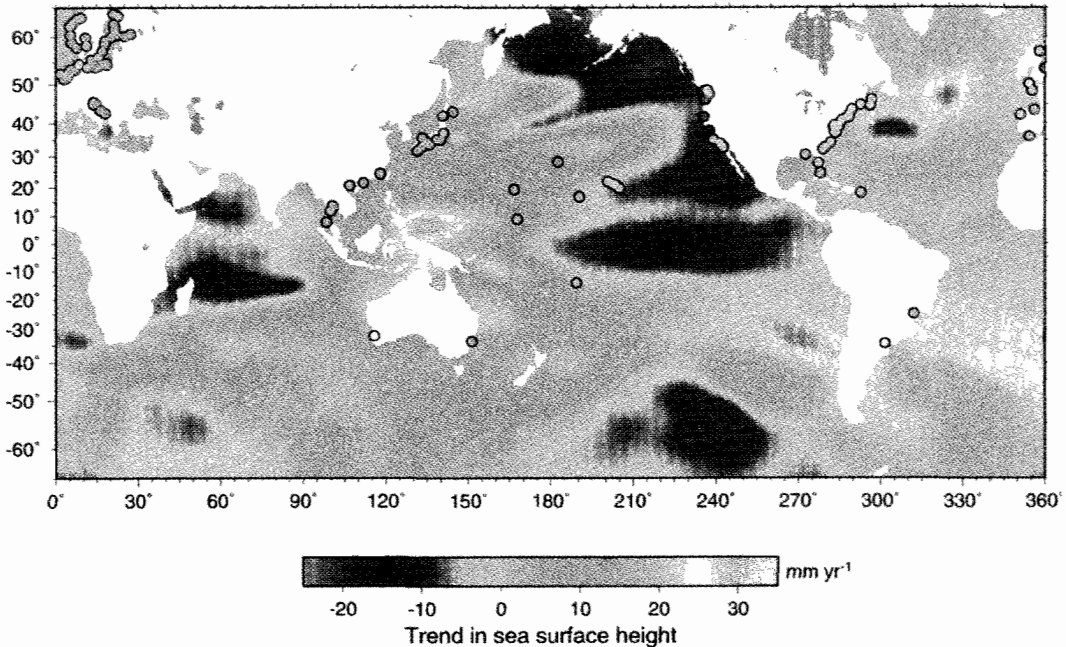


Fig. 5. Altimetry-derived Sea Level map from TOPEX/ Poseidon observations (1993 to 2003) (Leuliette *et al.*, 2004)

applies also to the Mascarene Islands and Zanzibar. Hence, it can be expected that even areas experiencing relative fall in sea level at the moment will, by the end of this century, experience a relative rise. The impact of the projected SLR on the economic and social development and environment on many of the island states is expected to be significant. The Third Assessment Report of the IPCC (IPCC, 2001b) identifies the following key issues among the priority concerns of SIDS:

- Change in sea level will have serious consequences for the social and economic development of many small island states. For some islands, the most serious consideration will be whether they will have adequate potential to adapt to SLR within their own national boundaries.
- Beach and coastal changes will be enhanced and SLR will increase the vulnerability of coastal environment by reducing natural resilience while increasing the economic and social “cost” of adaptation.
- Changes in sea-level are likely to affect landward and longshore migration of remnants of mangroves which provide some protection to the coasts and backshore infrastructure.
- SLR will adversely impact on the productivity and physiological functions of seagrasses, which would have a negative downstream effect on fish population that feed on these communities.
- Almost all settlements, socio-economic infrastructure and activities such as tourism, which are located at or near coasts will become highly vulnerable to future climate change and sea level rise.
- In some societies, CC and SLR could adversely affect community structures and assets such as important traditional sites of worship, ritual and ceremony.

The Barbados Plan of Action, which was formulated in 1995 in Barbados to address environmental issues of Small Island Developing States (SIDS) following the Rio Summit in 1992, also highlights that as population, agricultural land and infrastructure of SIDS tend to be concentrated in the coastal zone, any rise in sea level will have

a significant and profound effect on their economies and living conditions.

Vulnerability assessment to SLR has been conducted by some WIO island states. The principal impact of sea level rise for most coastal areas in Mauritius (Government of Mauritius, 1999) is land loss through submergence of lowlands and loss of wetlands as well as erosion of beaches. In the northern tourist zone, it is estimated that 1028 hectares of coastal land (0.5% of the island area) of high socio-economic value will be lost due to the projected sea level rise. It has been found that 26 km of beaches will be flooded with a 1m sea level rise. About 12.7 km of main coastal road and 24.5 km of secondary coastal road, which are critical to connect several villages along the coast, will be affected.

A Vulnerability and Assessment (V&A) study was conducted from 1996 to 1998 in Seychelles but this was based primarily on qualitative data and no projections of future infrastructure made. Among the impacts are:

- Enhanced erosion of shoreline and beaches.
- More severe coastal flooding especially during severe rainstorms and high tides.
- Salt intrusion in groundwater aquifers and coral island lens.
- Destruction of property and infrastructure located on the coastal plains and reclaimed land.
- Disappearance of several low-lying islands especially the sand cays.

A particular concern in the Maldives is the impact of climate change on the groundwater availability due to saltwater contamination of the fresh water lenses. The tourist industry, which relies heavily on the marine ecosystem, will be under serious threat. The islands of Maldives are reef-based and coral reefs serve as natural breakwaters. These are expected to degrade with rising sea temperature. The coral bleaching event of 1997/1998, which affected almost 90% of the reefs, is a severe warning of expected impact (Sheppard *et al.*, 2006). It is interesting to note that Møener *et al.* (2004), from findings based on a field study, suggested that a rapid sea level fall of approximately 30 cm could have occurred during the past few decades and most likely during the early 1970's. They attributed the fall to an increased

in monsoon-related evaporation over the Central Indian Ocean. However, Woodworth (2005), on the basis of an extensive set of oceanographic, meteorological and geological information, completely disagreed with the claim arguing that the Maldives instead do face an enhanced threat of inundation from a mean sea level rise in this century. The present study (Fig. 2f) has indeed shown that the Maldives did experience a small rise during the period of investigation.

Consequently, it is vital that sea level rise considerations be given much importance. Many countries including most SIDS in the WIO have not yet integrated CC and SLR issues in their sustainable development strategies. The main reason is that sea level rise is a long-term issue over several decades or longer. While these time scales are relevant to many decisions, we have to face the reality that policy-makers/politicians are more interested in shorter time scales. The challenge, therefore, is to embrace the timescales of change to conform to the time scales of decision-making.

On the other hand, it has been recognized (Chapter 17 of Agenda 21 of the Rio Summit in 1992) that the rate of change is uncertain. This uncertainty is an important barrier to action. One method by which uncertainties and risks associated with climate change and sea level rise can be integrated into the decision-making process has been developed (Nicholls *et al.*, 2000). It is through an adaptive management approach for flexible decisions that explicitly incorporate a "learning by doing" approach. Fundamental to the framework is the need for decision-makers to be guided such that they are able to make informed decisions, which consider the possible consequences of climate change and sea level rise. This implies that once a sea level network has been implemented, a regular assessment and evolution of the system should be made. Studies should be carried at regular intervals (every 5 years in normal situation and at shorter intervals in case of abnormal changes during extreme events) and the results widely disseminated to all stakeholders. This will ensure visibility and credibility and provide feedback to policy-makers on decisions they have taken. In this way, funding will be sustained to maintain the network over a long period.

CONCLUSIONS

The sea level network of the Western Indian Ocean Islands is vital for many purposes at national, regional and international levels. The data it is generating contribute significantly to monitor sea level variations in the region - an important prerequisite to understand coastal processes and beach erosion for decision-making on coastal protection. It is being used to determine regional sea level trends and changes associated with global weather pattern for long-term action. It is also a unique source of data for satellite altimetry calibration. Consequently, its sustainability and maintenance on a long-term basis is crucial. It is noted that, in the Caribbean region for example, a long term sea level monitoring programme has been given much attention. A Global Environment Facility (GEF)-funded programme for small island states entitled "Caribbean Planning to Global Climate Change Project" was initiated in 1996. A sea level and a climate monitoring network were established in 12 Caribbean countries (Volonté, 2000).

However, much concern has been raised at various fora about the degradation of the WIO network and lack of funding to keep it in good working order (e.g. IOC, 1991; IOC, 1994; PACSICOM Meeting, 1998). Recommendations made to maintain the network include:

- Replace old stations and obsolete gauges with new ones.
- Promote the installation of multi-parameter sea level stations.
- Upgrade communication facilities at gauge stations.
- Enhance maintenance capabilities of national technicians.
- Establish a regional programme for maintenance of the sea-level network.

It is gratifying to note that, in response to the above recommendations, in general and the requirement to obtain operational sea level data to enhance the early warning system in the WIO, the sea level station in Mauritius has been upgraded and the station at Rodrigues, damaged during the December 2004 tsunami, has been replaced with a more up to date system.

To conclude, it is appropriate to point out that the TOGA/SLC is a good model for data archival and access. Quality controlled sea level data are freely available on the website for studies. It is high time that a similar system be devised for other oceanographic datasets in the region in the fields of biological, chemical and physical oceanography and made available freely to scientists and students. Results of the research could be valuable in decision-making to preserve the marine environment and exploit marine resources in a sustainable way. UNEP (UNEP, 2003) is currently implementing the Africa Environment Information Network programme to enhance the capacities of countries in the region to generate a set of comprehensive environmental data and make it available to scientists and decision makers for research and Integrated Environmental Assessment and Reporting. There is a long way to go in reaching this goal, but there is hope that eventually a comprehensive set of environmental data will be easily accessible in the public domain on websites such as TOGA/SLC to monitor environmental changes.

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