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Importance of coastal sea level monitoring for Madagascar

Summary for policy makers

September 2021

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C-RISe COASTAL RISK INFORMATION SERVICE

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Importance of coastal sea level monitoring for Madagascar

Key messages:

Global Mean Sea Level (GMSL) has risen 20cm since 1900. Regionally sea levels are rising at different rates.

Sea level rise increases the likelihood of coastal erosion and flooding, affecting lives, livelihoods and infrastructure.

The accurate measurement of sea level is essential for tidal prediction, but there are few operational tide gauges or long term tidal records in Madagascar.

Since 1992 sea level has been measured from altimeters on satellites and these data can be used to understand how sea level is changing regionally.

Although tide gauges and satellite altimetry measure sea level differently, they can be used in combination for accurate coastal sea level and tidal prediction.

Ideally all coastal and island states would operate a network of long term tide gauges, which would contribute to local and global efforts in understand changing sea levels.

Improved information on sea-level and sea-level variability will result in enhanced safety in navigation and coastal activities (through better knowledge of tides), more accurate modelling of extreme events (such as storm surges associated with tropical cyclones), and will support better planning and management of the coastal zone through improved knowledge on long-term sea-level change.

What affects coastal sea level and why is it important to understand it?

The sea level at the coast varies continually with the tides and weather and is increasing over time due to climate change impacts. In some locations sea level is also changing due to changes in land height caused by subsidence and erosion. Global mean sea level (GMSL) is currently increasing at a rate of 3.58±0.48 mm yr^{-1}, primarily due to ocean warming (thermal expansion of water) and the melting of land ice (IPCC, 2019). Understanding coastal sea level is important for safety, navigation and infrastructure planning. Rising sea levels along with additional climate change-induced changes in tidal range and extreme events, are increasing risks to coastal populations and habitats.

The developing nations of the Southwest Indian Ocean (SWIO) are particularly vulnerable to sea-level extremes, due to intense tropical cyclone activity from October to March each year. Madagascar often experiences multiple tropical cyclones each year, with an average annual direct loss of $87 million (GFDRR, 2017). In 2015 tropical cyclone Chedza caused 68 fatalities and affected over 80,000 people (GFDRR, 2017). A recent study showed 26% of Madagascar's coastline to have high or very high levels of exposure to coastal hazards (Ballesteros & Esteves, 2021). It is projected that the average intensity of tropical cyclones will increase, that rising mean sea levels will contribute to higher extreme sea levels associated with tropical cyclones, and that coastal hazards will be exacerbated (IPCC, 2019).

Sea-level monitoring sustained over several decades enables the evaluation of the combined statistics of the probability of both extreme tides and storm surges to improve predictability. These statistics are used by coastal engineers to design sea defences. Long-term records also enable the estimation in long-term trends in global sea level associated with climate change. Understanding long-term change is particularly important as the risk of inundation increases when storm surges and high tides are superimposed on increased mean sea level. However, financial limitations make it impractical for countries such as Madagascar to install and maintain tide gauges at all points of interest along their coastline.

Longer-term sea level variability, including trends associated with climate change, can be derived from satellite altimetry. Analysis of sea level data from the C-RISe project (c-rise.info) has indicated that sea level in the SWIO is rising at up to 6 mm yr^{-1}, almost twice the rate of the global average (Figure 1).

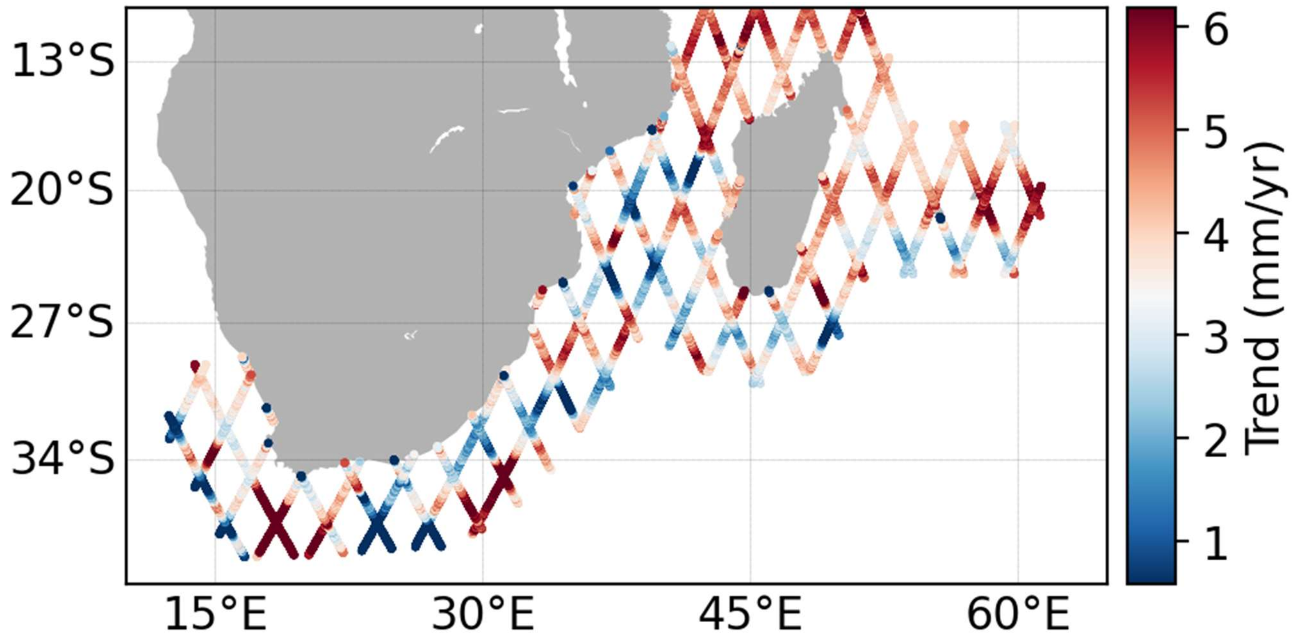


Figure 1. Sea level trend from Jason satellite altimetry (2002-2021). Note that white represents 3.5mm, the trend is wholly positive

How is coastal sea level measured?

Coastal sea level is traditionally measured using tide gauges. Automatic gauges have been in use for about 200 years. Although some early model float gauges are still in use, modern gauges use either underwater pressure transducers, or above water radar or acoustic sensors. Tsunami monitoring gauges use a combination of both technologies for added resilience. These tide gauges all have common attributes in that they measure the sea level at a single fixed point on the coastline, relative to a local datum on the land (relative sea level), with a high frequency (hourly data is usually made available). Recently tide gauges using Global Navigational Satellite Systems (GNSS) have also been developed (Geremia-Nievinski et al., 2020). Like traditional tide gauges, these also measure from a fixed point at a high frequency, but they measure absolute sea level (relative to the geoid).

Since 1992 sea surface height has also been measured from satellites, using altimetry (Cipollini et al., 2017). Satellite altimetry measures the absolute sea level (relative to the geoid, like GNSS), but, as the satellites circumnavigate the globe, the frequency of measurement is much lower (once every 10 days for the Jason series of satellites). Lower frequency of measurement means that satellite altimetry cannot be used to measure short term changes in sea level, such as tides. However, because they are not fixed at a single point, satellite altimetry gives information about sea level change over a large area. Satellite altimetry data is freely available and does not have the maintenance costs associated with tide gauges.

Sea level monitoring in Madagascar

There have been tide gauges installed at four locations along Madagascar's coast, however, only one of these, Toamasina, is currently operational. The Toamasina tide gauge was installed by the French agency, Service Hydrographique et Océanographique de la Marine (SHOM), in 2010 as part of the tsunami monitoring system. It is overseen by the Madagascar Metrological Office (Direction Général de la Météorologie, DGM) and data are made available through the International Oceanographic Commission (IOC). There is a long term sea level record available for Nosy Be, but tide gauges at Toliara and Taolagnaro had poor quality data, with many gaps due to technical issues (Razakafoniaina, 2001).

Issues in measuring coastal sea level for developing states

In addition to the susceptibility of tide gauges to tropical cyclones, there are several reasons that tide gauges are non-operational in developing states. The main four reasons, identified by Hoguane (1999), are:

- Lack of equipment (and difficulty acquiring replacement parts (Mundlovo et al., 2007);
- Lack of qualified maintenance personnel;
- Lack of funds to maintain tide gauges;
- Difficulty in accessing remote tide gauges due to poor transport infrastructure, poor roads and insurgency.

It has also been recommended that, in order to achieve a fully operational national tide gauge network and make data available to end users, some national capacity development is required (Razakafoniaina, 2001)

A good understanding of all hazards related to sea level requires long-term, high-quality observations, which can only be assured through dedicated funding and skilled local operators (Hibbert, 2021). The use of satellite altimetry data could alleviate some of these issues, providing freely available sea level data, with no equipment to maintain.

How can developing states use satellite altimetry data supplement tide gauge data?

The use of a combination of satellite altimetry and tide gauge data, particularly in developing coastal and island states, will enhance knowledge of coastal sea level and how it is changing, so that lives, infrastructure and livelihoods can be protected.

Tide gauge measurements can be compared with altimetry data through absolute calibration at selected sites, or regional or global comparison using a network of gauges (Ablain et al., 2017). This was carried out in the SWIO during the C-RISe project using data from tide gauges in Mozambique, Madagascar and South Africa (see Box 1).

Altimetry data provides an extended time series of sea level data where tide gauge data records have gaps due to maintenance issues or where they have stopped operating. Altimetry also provides data for locations without tide gauges, giving information on longer-term sea level variability, including the trends associated with climate change. However, altimetry gives absolute sea level measurements (relative to the geoid), and this requires both correction for vertical land motion as well as 'ground-truthing' to some known fixed point on land if they are to be meaningful for planning and mitigation purposes.

Where there are no long term tide gauge record available, ground-truthing can be achieved through the use of GNSS receivers. If these are co-located with conventional tide gauge sensors (measuring relative to a fixed point on land) in a temporary tide gauge (see Box 2) the short-term tide gauge and GNSS measurements can be connected to satellite altimetry, which can then substitute for long-term observations from tide gauge data.

Box 1. C-RISe Validation

The C-RISe project (c-rise.info) provided processed altimetry data from the Jason-1, -2 and -3 satellites from 2002 to 2021. These data were validated, using software developed for the project, against existing tide gauges, where sufficient data was available. In Madagascar the tide gauge at Toamasina (data available from 2010 to 2020) was used (Figure 2).

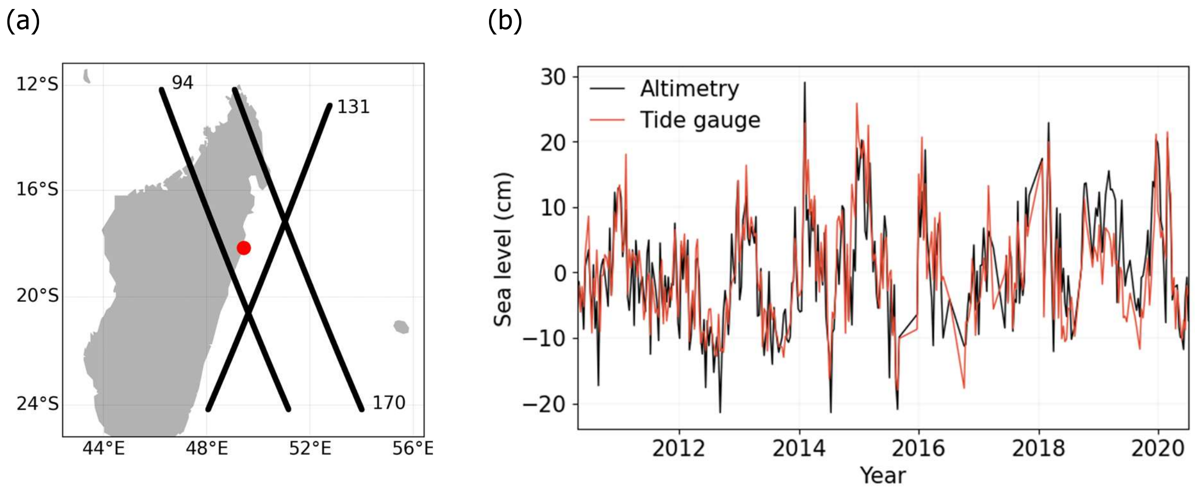


Figure 2. (a) Location of tide gauge at Toamasina (red dot) in relation to the Jason satellite tracks (black lines) and (b) comparison of sea level measured by altimetry and tide gauge (correlation: 0.82, rms difference: 0.05, distance from coast: 6.40 km).

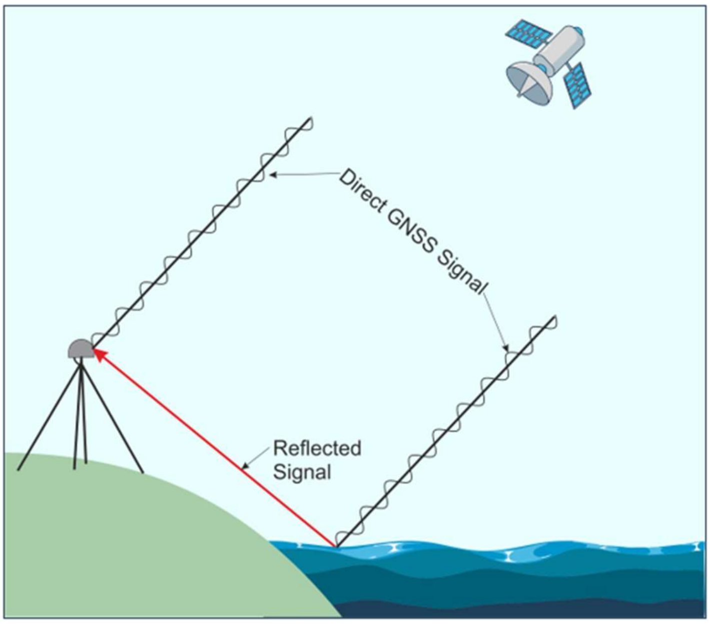
Conclusion and recommendations

The sea level at the coast varies continually and is increasing over time due to climate change impacts. Sea level in the SWIO is rising at up to 6 mm yr^{-1} (Figure 1). Understanding coastal sea level is important for safety, navigation and infrastructure planning. Risks to coastal populations and habitats are increasing with rising sea levels and additional climate change-induced changes in tidal range and extreme events.

Coastal sea level can be measured by tide gauge or satellite altimetry. Tide gauges provide high frequency measurements at a fixed location and are expensive to install and maintain, whist satellite altimetry provides low frequency measurements globally, with data freely available. Ideally these two technologies should be used in combination to enable good understanding of coastal sea level over a wide area at an affordable cost. This may involve the deployment of temporary tide gauges fitted with GNSS technology to obtain tidal parameters, characterise non-tidal sea level variability and validate satellite altimetry. This will lead to improved tidal predictions and sea level monitoring as well as a good understanding of long-term climate change-related sea level rise, enhancing safety, navigation and infrastructure planning whilst protecting coastal populations and habitats.

Box 2. Short-term relocatable tide gauge with GNSS receiver - "Portagauge"

The "Portagauge" concept combines with a new design low cost, re-deployable tide gauge using GNSS technology (Figure 3). This combination employs an innovative technique known as GNSS interferometric reflectometry (GNSS-IR), which supplies high frequency data relative to the same reference ellipsoid as satellite altimetry, so the two datasets are both complementary and directly comparable. This offers an affordable model for a sea-level monitoring system for developing island or coastal nations with limited resources, and a flexible and lower cost alternative to the previous approach which would be the installation of more traditional design tide gauges at fixed locations for a longer period of time (40 years to establish a tidal record). This could have a significant benefit for developing coastal and island states, with a limited number of conventional tide gauges and short term or intermittent records.



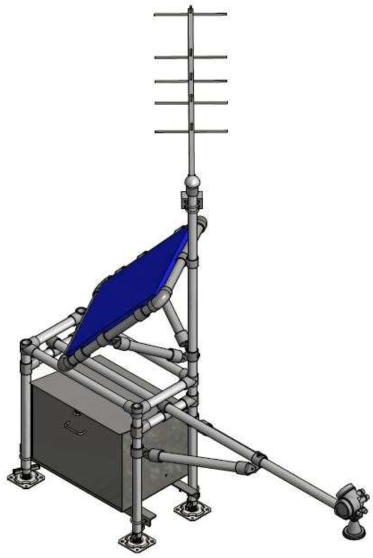


Figure 3. (a) Measuring GNSS-IR sea level and land movement relative to the ellipsoid and (b) the relocatable tide gauge or "Portagauge"

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Project funded by:

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