PASS-SWIO

Portagauge and Satellite Sea Level Monitoring System for the Southwest Indian Ocean

Sea Level Variability Report

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1. Introduction

This document provides an overview of tidal and non-tidal sea level variability in the region of Madagascar, from model, tide gauge and satellite altimeter data. The report uses new analysis carried out for the PASS-SWIO project and refers to results from other relevant analyses.

The objective of the overview is to identify regions where the patterns of variability are coherent, and where they are different, to support the identification of future tide gauge locations in the development of a sea level monitoring system for the Southwest Indian Ocean, explored in the Implementation Road Map (D4.1).

2. Tidal Variability

There is limited availability of reliable long-term in situ tide gauge data for Madagascar. There have previously been tide gauges installed at four locations along Madagascar's coast (Becker, 2021). A tide gauge was installed at Toamasina by the French agency, Service Hydrographique et Océanographique de la Marine (SHOM), in 2010 as part of the tsunami monitoring system, but it ceased to operate in March 2022, due to development at the port. PASS-SWIO installed a NOC Portagauge close to the location of the SHOM Gauge in June 2023.

A long-term sea level record is also available for Nosy Be (for 1958 to 2014), but that tide gauge is no longer operational. Other tide gauges were installed at Toliara and Taolagnaro but had poor quality data with many gaps due to technical issues (Razakafoniaina, 2001). This analysis is therefore based on modelled tidal parameters. Figure 1 illustrates the variability in the amplitude of the M2 tidal constituent from the GOT99.2 model (Ray, 1999).

Looking at the Madagascar coast in Figure 1 it can be seen that the amplitude of the M2 constituent is significantly higher on the west coast of Madagascar and in the Mozambique Channel (> 100cm), than it is on the east coast (< 30cm). From this we can anticipate a different nature of tidal sea level variability on the East and West coasts of Madagascar.

Tidal parameters for locations around the Madagascar coast were extracted from the POLTIPS model for the C-RISC project (UKRI, 2024). Tidal parameters for five of these locations, illustrated in Figure 2, are given in Table 1.

The largest tidal range (4.03m) is for Mahajanga in the northwest, this range decreases for locations to the south on the west coast (Morondava 3.91m; Toliara 2.96m). The tidal range is much lower on the east coast: 0.72m at Toamasina and 0.55m at Mananjary. Note that these tidal ranges are not referenced against a local datum, but against a nominal mean sea level.

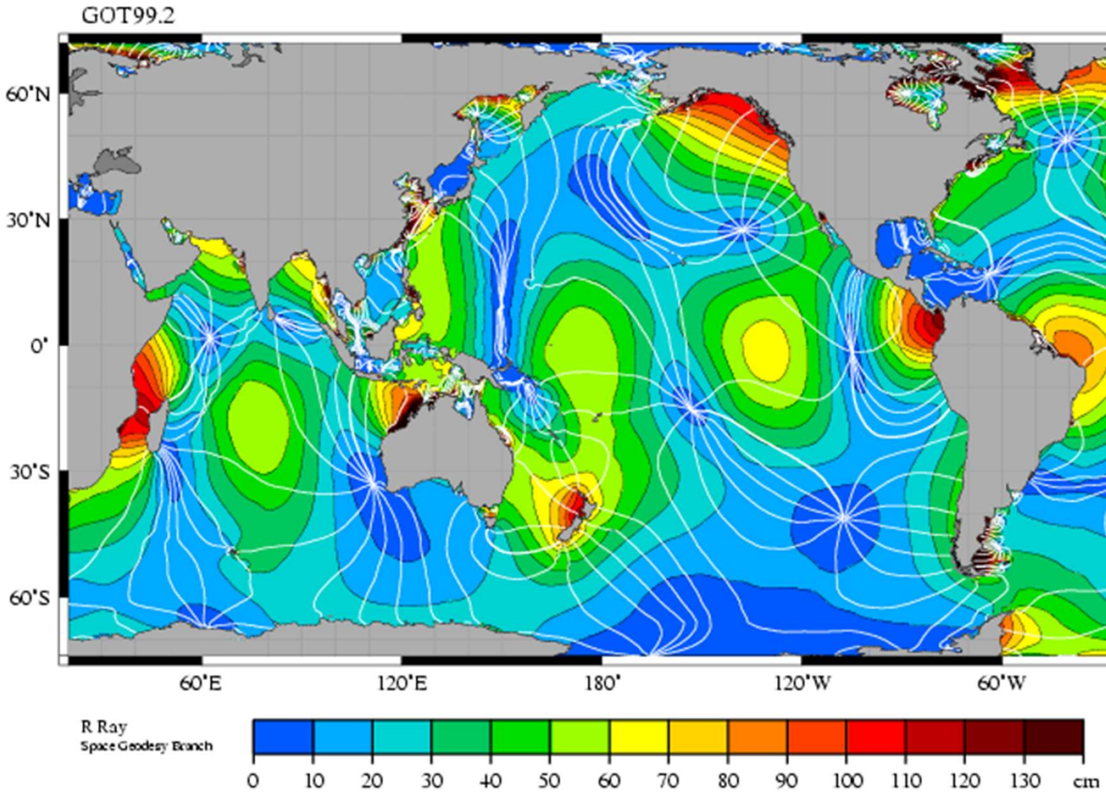


Figure 1. Amplitude of M2 tidal constituent, from GOT99/2 tidal model. NASA/GSFC

Table 1: Tidal Parameters for five different locations on the Madagascar coast. Tide model constituents from POLTIPS.

Location	**Mahajanga**	**Morondava**	**Toliara**	**Toamasina**	**Mananjary**
Highest Astronomical Tide	2.07m	1.96m	1.49m	0.36m	0.27m
Lowest Astronomical Tide	-1.98m	-1.95m	-1.47m	-0.37m	-0.29m
Maximum tidal range possible	4.03m	3.91m	2.96m	0.72m	0.55m
Mean High Water Springs	1.69m	1.66m	1.24m	0.28m	0.20m
Mean High Water Neap	0.49m	0.43m	0.31m	0.11m	0.05m
Mean Low Water Neap	-0.49m	-0.43m	-0.31m	-0.11m	-0.05m
Mean Low Water Springs	-1.69m	-1.66m	-1.24m	-0.28m	-0.20m

Figure 2. Locations for Table 1 for which tidal constituents were extracted from POLTIPs.

3. Non-Tidal Variability

3.1. Introduction

We consider three different aspects of non- tidal variability: long term trends, seasonal variability (annual and semi-annual cycles) and storm surges resulting from the landfall of tropical storms and cyclones.

The main characteristics of non-tidal variability are:

- Long Term Trend (3-4 $mmyr^{-1}$) – 15-20cm over 50 years
- Annual (6 - 10cm) and Semi-Annual (< 2cm) cycles

- Storm surges (up to 2 m), Tsunami (5.4m maximum runup from 2004 Boxing day Tsunami)

These ranges can be compared to the tidal ranges of 3-4 m for the west coast and 0.5-1 m on the east coast. The range of the annual cycle (5-10 cm) is much lower than the tidal range, even for the east coast. Storm surges however can be larger than the normal tidal range for the east coast, and of the same order of magnitude for the west coast. Whilst the long-term trend may seem small (3-4 $mmyr^{-1}$) compared to the tidal range, it will have a significant impact in the medium term (1.5-2 m over 50 years), especially on the east coast where erosion is already a problem.

3.2. Long Term Trends

It is well established that global sea level is increasing as a result of climate change. According to the latest measurements, global mean sea level has increased by 3.6 $mmyr^{-1}$ since 1993 (Figure 3). However, this trend is not globally uniform, and varies between locations. The ESA Sea Level CCI project (Cazenave et al., 2022), Figure 4, illustrates how the trend varies across the oceans and at the coasts.

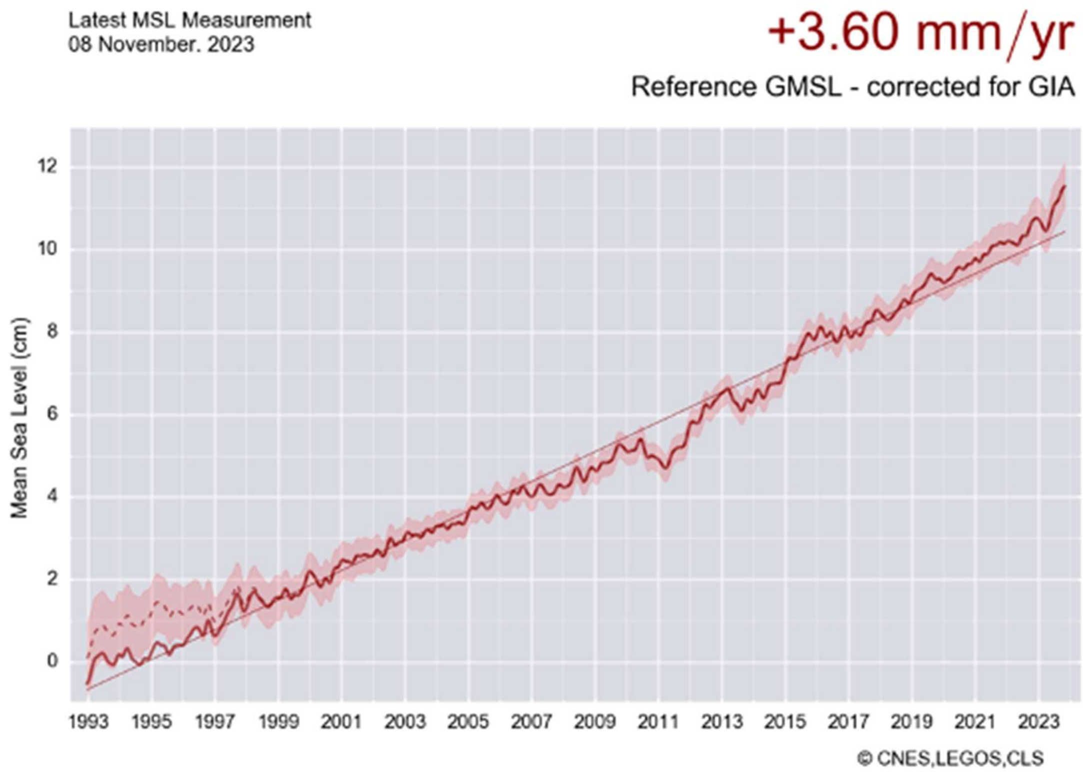


Figure 3. Global mean sea level measured by satellite altimeter (Topex/Poseidon, Jason-1, Jason-2, Jason-3 and Sentinel-6 MF missions), from January 1993 to present after removing the annual and semi-annual signals and applying a 6-month filter. Copyright CNES, LEGOS, CLS.

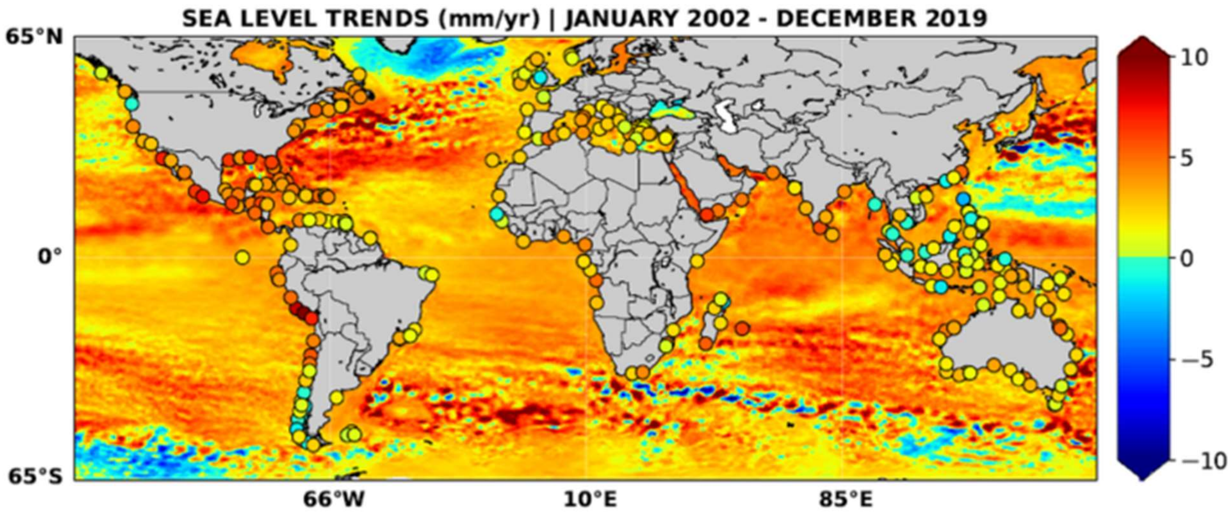


Figure 4. Coastal mean sea level trends (average over the first 2 km along the track) computed over January 2002 to December 2019 for the 251 virtual stations located at less than 3.5 km from the coast. The background map represents the sea level trends over the same time span. (Cazenave et al., 2022)

Looking more closely at the Southwest Indian Ocean in the region of Madagascar (Figure 5) the annual increase ranges between 3 and 5 mmyr^{-1} offshore and varies between 2.1 mmyr^{-1} (south-east) and 3.9 mmyr^{-1} (north-west) at the coast. These differences in sea level trends around the Madagascar coast are due to variations in patterns of ocean circulation.

Thus, from analysis of 20 years' altimeter data, the sea level at the Madagascar coast is estimated to have risen by 42 – 780 mm over that time period. These trends calculated from satellite altimeter data are expressed relative to a mean sea level, so do not include any changes in the land at the coast (for instance vertical land movement and erosion).

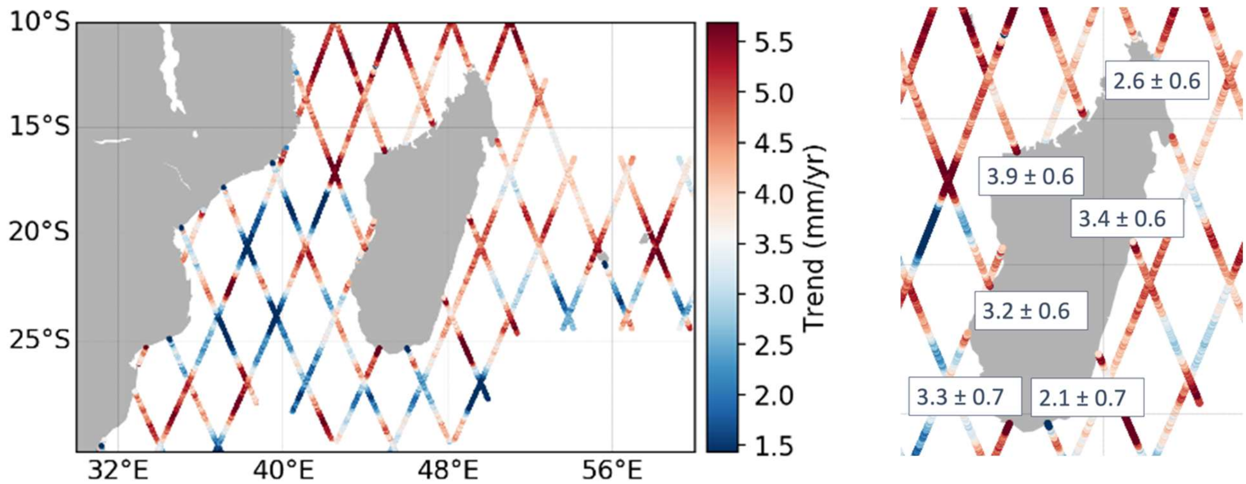


Figure 5. (left) Annual increase in sea level (2000-2020) calculated from satellite altimeter data (Jason-1, Jason-2, Jason-3), (right) Zoom of right panel to Madagascar coast. Inset values are annual increase within 3km of the coast, calculated for the ESA CCI+ sea level project (Cazenave et al., 2022).

Analyses of GPS data indicate a range in vertical land movement across Madagascar of 0 mmyr^{-1} (in the south) to –1 mmyr^{-1} (in the north) (Figure 6, Hammond et al. 2021). Thus, the sea level change relative to the coast in the north may be increased by 1 mmyr^{-1}, whereas in the south, land movement has no impact. Tide gauges equipped with GNSS technology will allow this effect to be estimated more accurately.

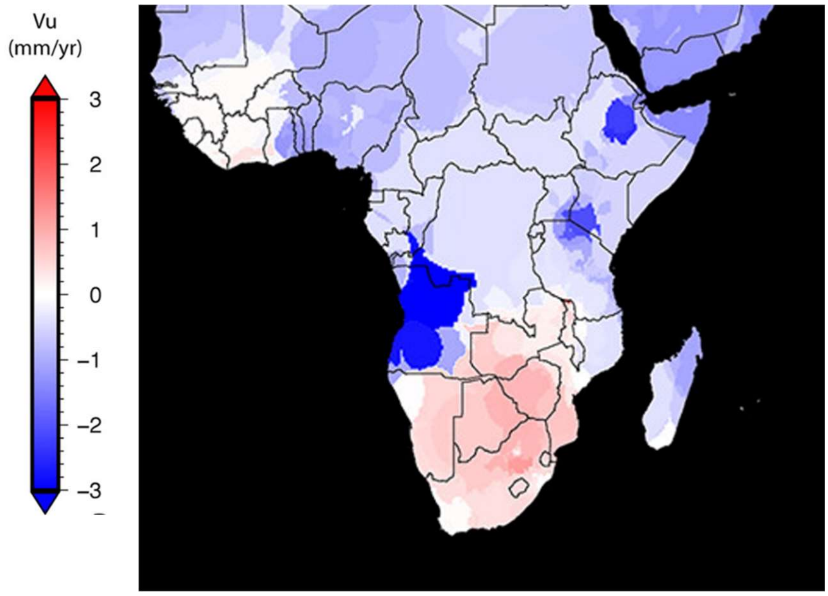


Figure 6. GPS imaging of vertical movement of land, blue is downward, red is upward (see key on left).

Under current climate modelling scenarios, these increasing trends in sea level are expected to continue, and potentially accelerate with higher emissions and over longer time periods (Oppenheimer et al, 2019).

Over coming decades, sea level rise, coupled with storm surges and waves will exacerbate coastal inundation and cause shorelines to retreat along sandy coasts (Oppenheimer et al, 2019).

It is therefore important to have accurate long-term in-situ sea level measurements, georeferenced against fixed vertical datums and linked to satellite data references through GNSS at different locations to confirm the satellite derived values, and to understand the impact of vertical land motion.

3.3. Seasonal Cycles

Satellite altimeter data can also be used to extract the characteristics of seasonal cycles in sea level, driven by changes in winds and ocean circulation. Figure 7 illustrates the characteristics of the annual cycle in sea level for the Southwest Indian Ocean, and for three locations on the Madagascar coast (Toamasina, Morondava and Mahajanga). It can be seen that the amplitude of the annual cycle varies across the locations, from 6cm to 10cm. Therefore, this is unlikely to be a significant factor for most coastal applications. The amplitude of the semi-annual cycle (not shown) is even smaller, at under 2cm at all locations.

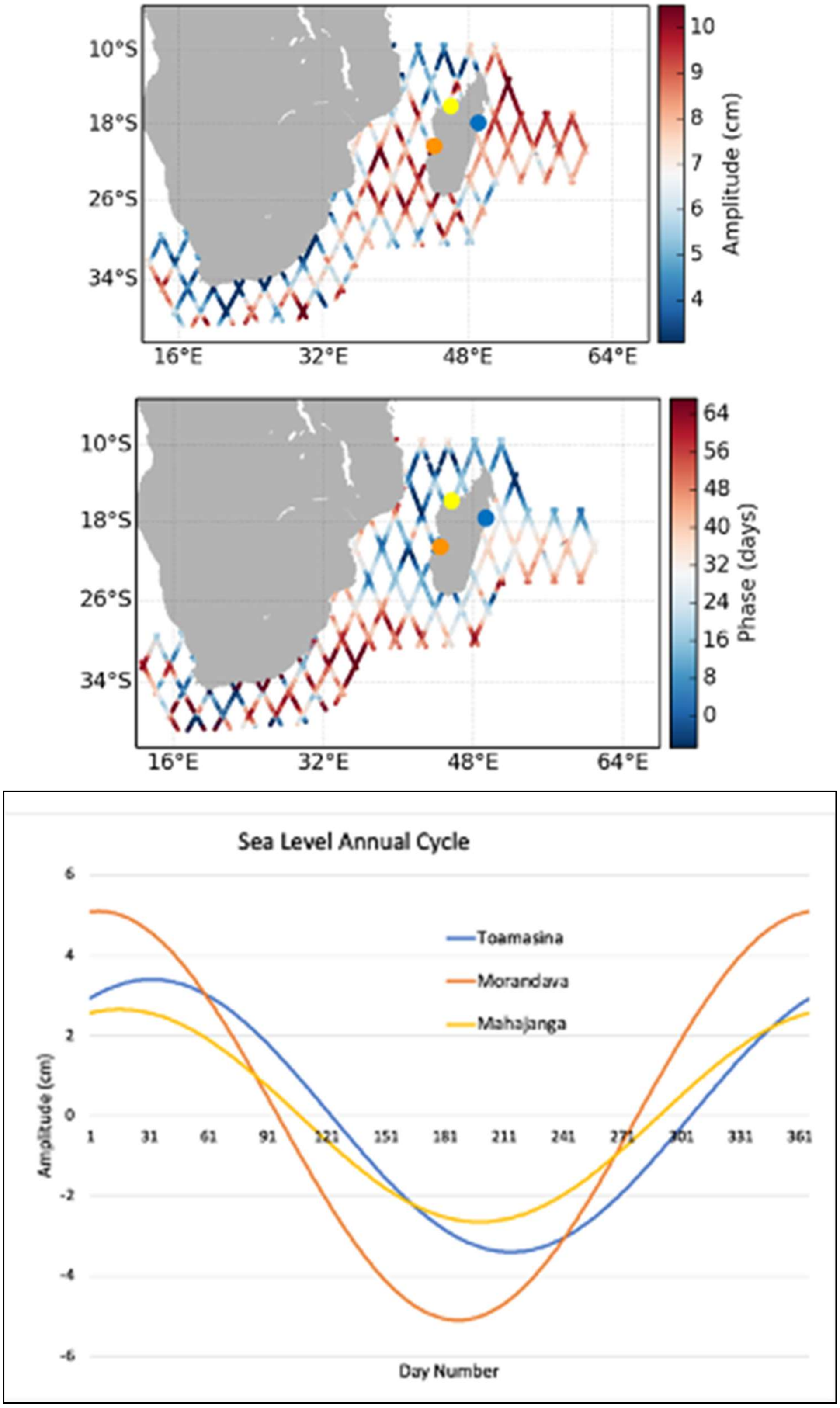


Figure 7. Amplitude (top) and phase (middle) of the annual cycle of sea level, derived from an analysis of satellite altimeter data (Jason-1, Jason-2, Jason-3). The phase is given as the day number in the year when the amplitude is at a maximum. (bottom) The amplitude (in cm) of the annual cycle in sea level, against day number, for three locations in Madagascar: Toamasina, Morondava and Mahajanga.

3.4. Extreme Events (Tropical Cyclone Storm Surges, Tsunami)

Tropical Cyclone Storm Surges

Finally, we consider sea level variability from extreme events, the major impact on the Madagascar coast being the high winds and storm surges associated with tropical cyclones. Very high precipitation is also an important impact of cyclones on the Madagascar population, especially inland where it causes flooding and landslides.

The number and intensity of tropical storms in the Southwest Indian Ocean varies from year to year, but on average, in the order of 10 named storms occur each year and one of those will make landfall on Madagascar (Langlade, 2013). The associated storm surge can be up to 2m (GFDRR, 2016). Figure 8 (Langlade, 2013) shows the tracks of historical cyclones and suggests that most (85%) cyclones make landfall on the east coast, and most of these between 15°S and 20°S.

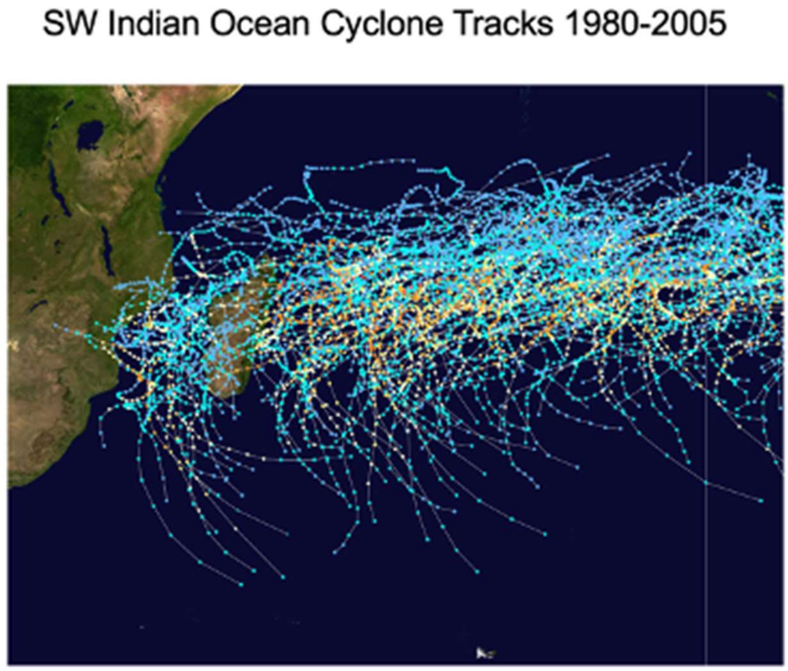
The NOC modelled the storm surges from 66 named tropical storms between 1990 and 2015, not all of which made landfall on Madagascar, and plotted the residual sea surface height (total storm surge height minus tide) at each model grid point. Figure 9 shows the maximum residual sea surface height for three example storms, and the combined maximum residual height for all storms. The combined plot shows there is a risk to storm surge at all coastal locations, with perhaps maximum risk at the north-eastern and central western coasts.

According to a report by the Global Facility for Disaster Relief and Recovery (GFDRR, 2016), the hazard from storm surge is greatest at the northern end of Madagascar, where the storm surge can exceed 2m.

Tsunami

The GFDRR classifies the risk to the Madagascar coast from Tsunami as medium (GFDRR, 2020). This means there is more than a 10% chance of a potentially damaging tsunami occurring in the next 50 years. The north, east, and southern coasts are classified as being at medium risk, the western coast from Morombe north to Ambanja is classified as low risk.

Okal et al (2006) reported that the maximum runup on the Madagascar east coast following the 2004 Boxing Day tsunami was 5.4m at Betanty in the southeast. No casualties were reported, though there was some damage to infrastructure (roads).



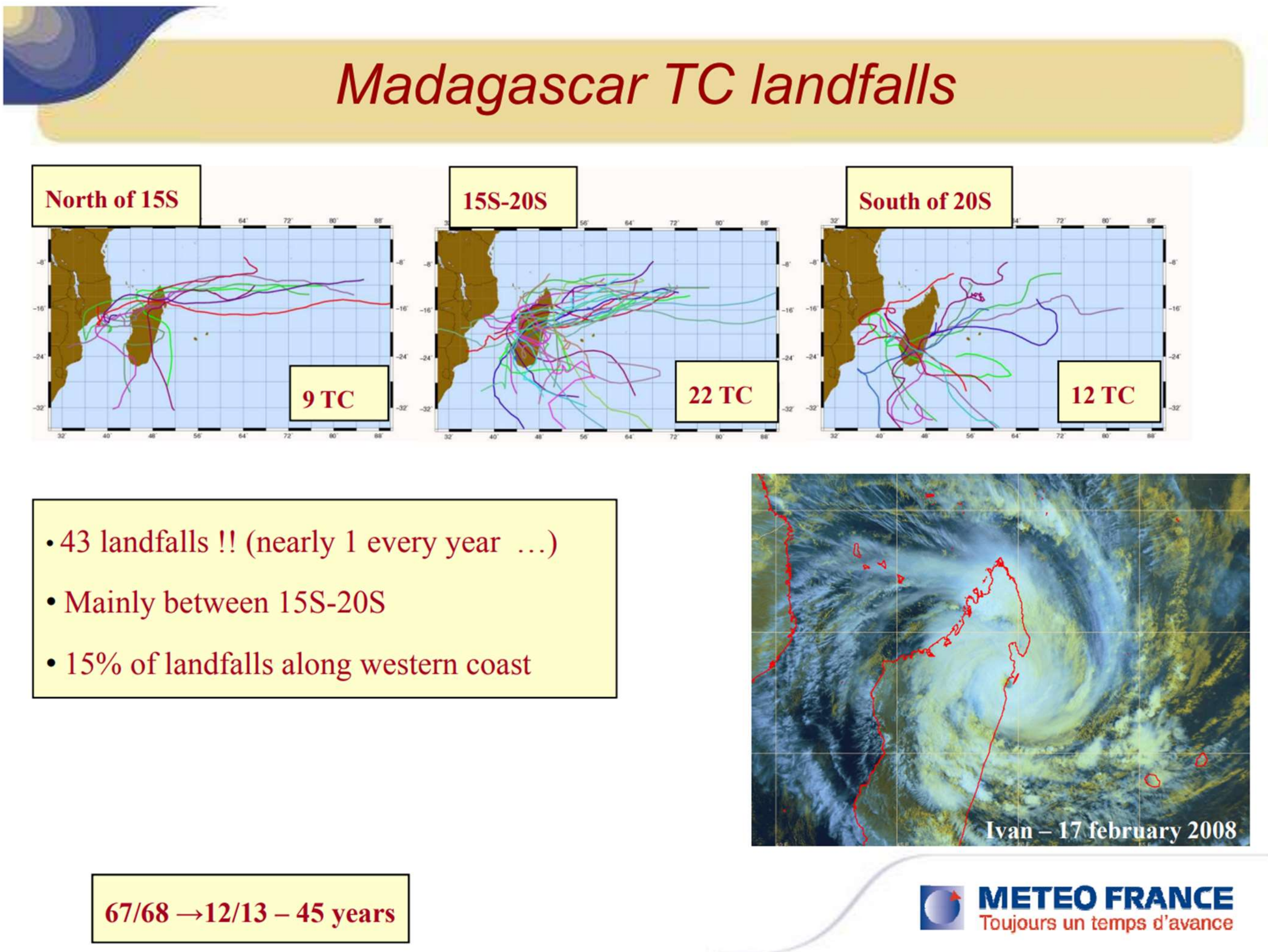


Figure 8. (Top) Tracks of SW Indian Ocean cyclones between 1908-2005. (Bottom) Analysis of Tropical Cyclone landfalls (Langlade, 2013)

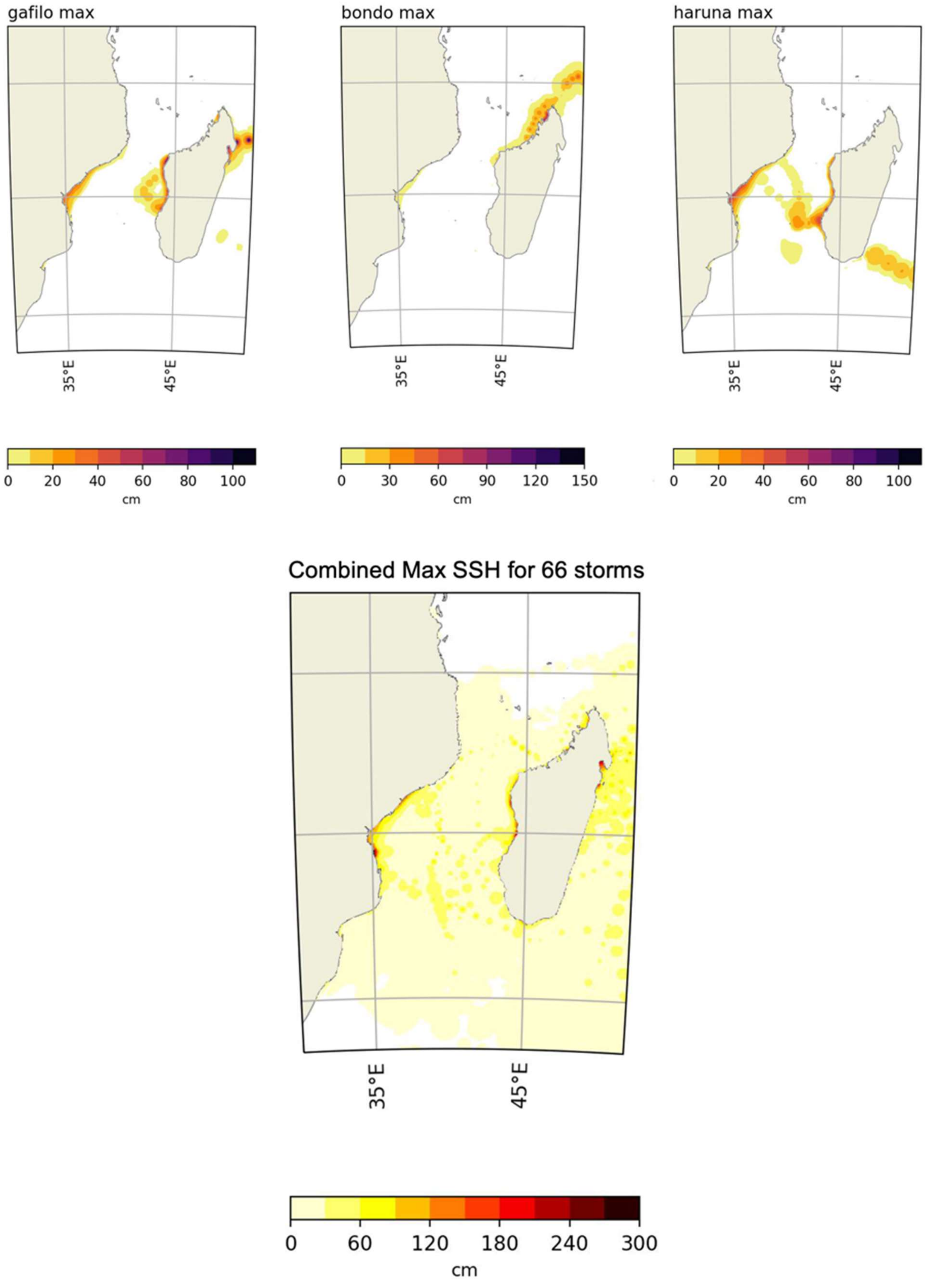


Figure 9. (Top) Maximum modelled residual sea surface height from three storms, (Bottom) Combined maximum residual sea surface height for 66 storms between 1990 and 2015. (NOC C-RISC, unpublished).

4. Conclusions

This technical note has provided an analysis of the characteristics of sea level variability for the Madagascar coast. The main findings are:

- Tidal parameters vary around the coast of Madagascar. The tidal range varies from 4m in the northwest to less than 1m on the east coast.
- Long term trends in sea level also vary around the coast of Madagascar, from 3.9 $mmyr^{-1}$ in the northwest to 2.1 $mmyr^{-1}$ in the southeast. This does not include the effect of any vertical land movement at the coast, which should be investigated.
- The seasonal cycle in sea-level is of the order of 5-10cm, and so is not significant compared to other factors.
- The storm surge associated with tropical cyclones can be up to 2m. The impact of storm surges can be felt at all locations on the Madagascar coast, but analysis of historical storms indicates the northeast coast and central west coast are most at risk.
- The maximum runup from the 26/01/2004 Indian Ocean Tsunami was 5.4m at Betanty in the south.

5. References

Becker, A. (2021) Importance of coastal sea level monitoring for Madagascar. Summary for Policy Makers. Document for the C-RISe project [available online] https://c-rise.info/c-rise/sites/c-rise/files/documents/Sea%20Level%20Monitoring%20Madagascar.pdf

Cazenave A., Gouzenes, Y., Birol, F., Leger, F., Passaro, M., Calafat, F.M., Shaw, A., Nino, F., Legeais, J.F., Oelsmann, J., Restano, M. and Benveniste, J. (2022) Sea level along the world's coastlines can be measured by a network of virtual altimetry stations. Communications Earth & Environment, 3, 117. https://doi.org/10.1038/s43247-022-00448-z

GFDRR (2016) Disaster Risk Profile: Madagascar, The World Bank, Washington DC [online] https://www.gfdrr.org/sites/default/files/madagascar.pdf (accessed April 2024)

GFDRR (2020) Madagascar, Thinkhazard! [online] https://thinkhazard.org/en/report/150-madagascar/TS (accessed April 2024)

Hammond, W.C., Blewitt, G., Kreemer, C. and Nerem, R.S. (2021) GPS Imaging of Global Vertical Land Motion for Studies of Sea Level Rise, Journal of Geophysical Research: Solid Earth, 126, 7. https://doi.org/10.1029/2021JB022355

Langlade, S. (2013) The SouthWest Indian Ocean cyclone basin, World Metrological Organisation [available online] https://severeweather.wmo.int/TCFW/RAI_Training/Cyc_Bassin_SWI_oct2013_LANGLADE.pdf (accessed April 2024)

Okal, E.A., Fritz, H.M., Raveloson, R., Joelson, G., Pančošková, P., Rambolamanana, G. (2006) Madagascar Field Survey after the December 2004 Indian Ocean Tsunami. Earthquake Spectra, 22(3_suppl): 263-283. https://doi.org/10.1193/1.220264

Oppenheimer, M., Glavovic, B.C., Hinkel, J., van de Wal, R., Magnan, A.K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R.M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B. and Sebesvari, Z. (2019): Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner, H-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. and Weyer N.M. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 321–445. https://doi.org/10.1017/9781009157964.006

Ray, R. (1999) A global Ocean Tide Model From TOPEX/POSEIDON Altimetry, GOT 99.2. National Aeronautics and Space Administration, Goddard Space Flight Center, Maryland. [available online] https://ntrs.nasa.gov/api/citations/19990089548/downloads/19990089548.pdf

Razakafoniaina, N.T. (2001) Sea Level Measurement and analysis in the Western Indian Ocean. National Report: Madagascar. International Oceanographic Commission [available online] https://gloss- sealevel.org/sites/gloss/files/publications/documents/madagascar_2001.pdf (accessed September 2021)

UKRI (2024) Coastal Resilience to flooding Impact through relocatable Storm surge forecasting Capability for developing nations (C-RISC) [online] https://gtr.ukri.org/projects?ref=NE%2FR009406%2F1 (accessed April 2024)

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