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View Abstract

Control of linear and non-linear vertical land motion on modern sea-level change (with implications for projections) across the Indian Ocean

Emmaline Martin[1], Luke Jackson[1], Sophie Williams[1]
(emmaline.a.martin@durham.ac.uk)

Durham University

[1]Department of Geography, Durham University, Durham, U.K, DH1 3LE.

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Introduction:

Vertical land motion (VLM) has key consequences for sea-level change[1] (SLC) at present and in the future, with a range of implications for the coast and coastal communities[2]. The Indian Ocean (IO; Figure 1) coastline supports 2.6 billion inhabitants[3] and its exposure is projected to increase[4]. VLM contributes to this increase by amplifying SLC through subsidence. VLM occurs across various spatio-temporal[5] scales (e.g. seconds to millennia[6], local to global[7]) and can be both linear (e.g. glacial-isostatic adjustment) and non-linear (e.g. seismicity and groundwater extraction)[8]. Recent syntheses of SL and VLM data address linear/non-linear effects but high uncertainty remains in the IO[8, 9, 10, 11].

Aim: to evaluate the role of VLM on SLC (1993 to 2024) by extracting linear and non-linear VLM signals from observations. We test the ability of SL data to record VLM by comparing an extraction method to colocated VLM sites.

Methodology:

1. Data Strategy

- Tide Gauges (TG, monthly records) from the Permanent Service for Mean Sea Level[9] are selected based on adherence to a set of indicated criteria (Figure 1).
- GNSS stations colocated with TGs are selected from Nevada Geodetic Laboratory (NGL)[10] with model offsets identified.
- Altimetry (A) data (Jet Propulsion Laboratory[12]) is extracted at nearest grid point (1° resolution) to TG (data sources depicted in Figure 2).
- For each colocated site and associated altimetry, the records were clipped to a common period with GNSS.

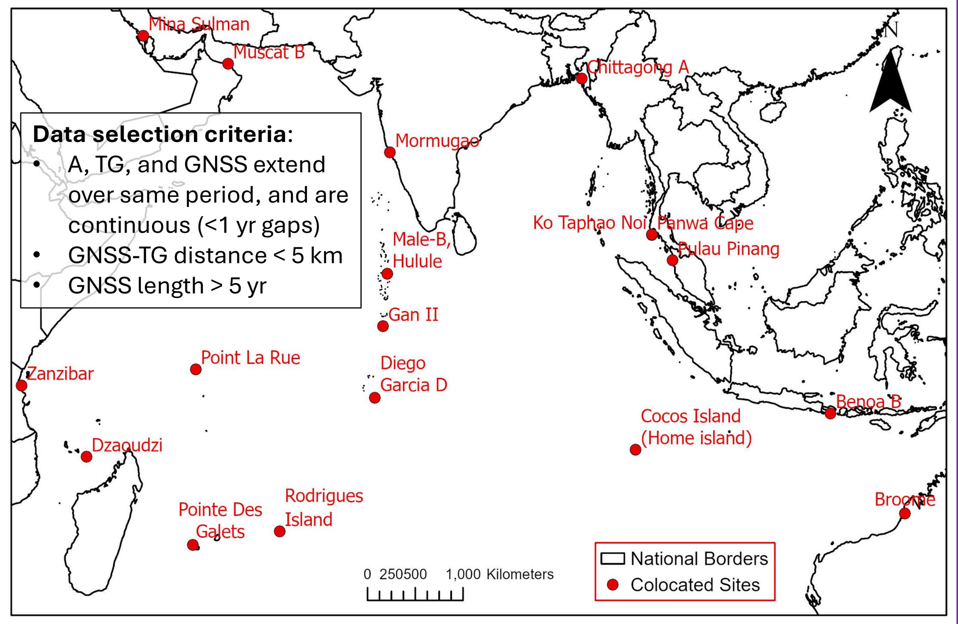

Figure 1: Map of colocated sites

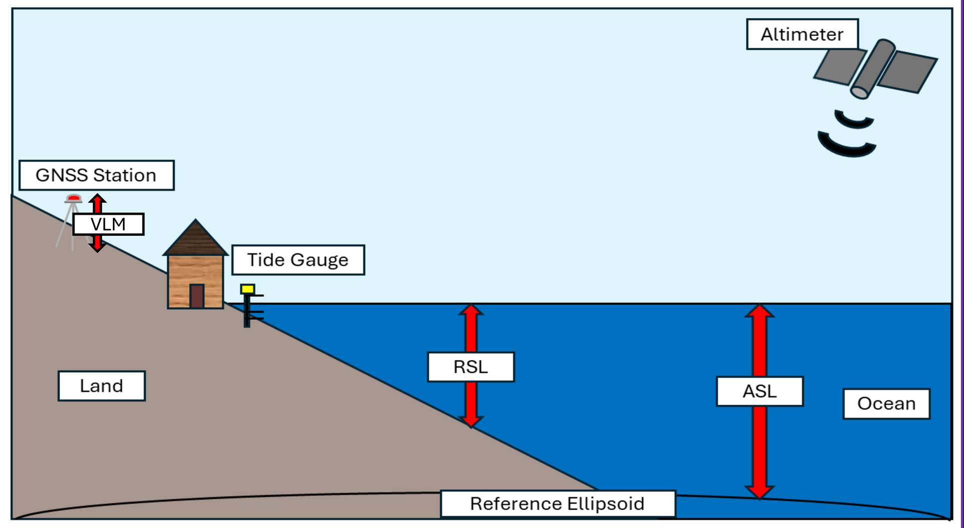

Figure 2: Schematic of data strategy.

2. Annual Cycle Correction

An annual cycle correction is applied to A and TG time series at each location to reduce inter-annual variability (e.g., atmosphere-ocean loading).

3. Linear analysis

The $\dot{VLM}_{ATG}$ dataset is produced by calculating the residual:

$$\dot{VLM}_{ATG} = \dot{ASL}_A - \dot{RSL}_{TG}$$

Where $\dot{VLM}_{ATG}, \dot{ASL}_A$ and $\dot{RSL}_{TG}$ are the rates of VLM, altimetry, and tide-gauge time series.

4. Non-linear analysis

We evaluate VLM_{ATG} at each time step to assess the capacity of the method to resolve non-linear VLM.

$$VLM_{ATG} = ASL_A - RSL_{TG}$$

5. Testing Budget Closure

$\dot{VLM}_{GNSS}$ (from NGL regression model[10]) and VLM_{GNSS} is used to test linear and non-linear budget of $\dot{VLM}_{ATG}$ and VLM_{ATG} respectively.

We assess misfit (linear) and RMS (non-linear) of VLM_{ATG} and VLM_{GNSS} records.

6. Spatial extension across IO

We apply the linear VLM method to all TGs overlapping with A (5 yr < |t| < 31 yr)

Results:

1. Evaluation of linear rates

- Misfit (Figure 3) shows scatter (-21 to +16 mm/yr) between VLM_{ATG} and VLM_{GNSS} rates, with mean misfit (-1.5 mm/yr) slightly underestimating true linear VLM.
- RMS (1.3±0.7 mm/yr) shows good agreement of misfits. Panwa Cape and Pulau Pinang (Figure 3) have largest uncertainties (±6 and ±5.6 respectively).
- Cocos Islands (COCO; Figure 4) shows a linear downward trend, indicative of VLM subsidence over time.
- Scatter across the VLM_{ATG} record indicates additional sources of VLM uncertainty (e.g. Cocos Islands as the VLM_{ATG} exceeds VLM_{GNSS} rate).

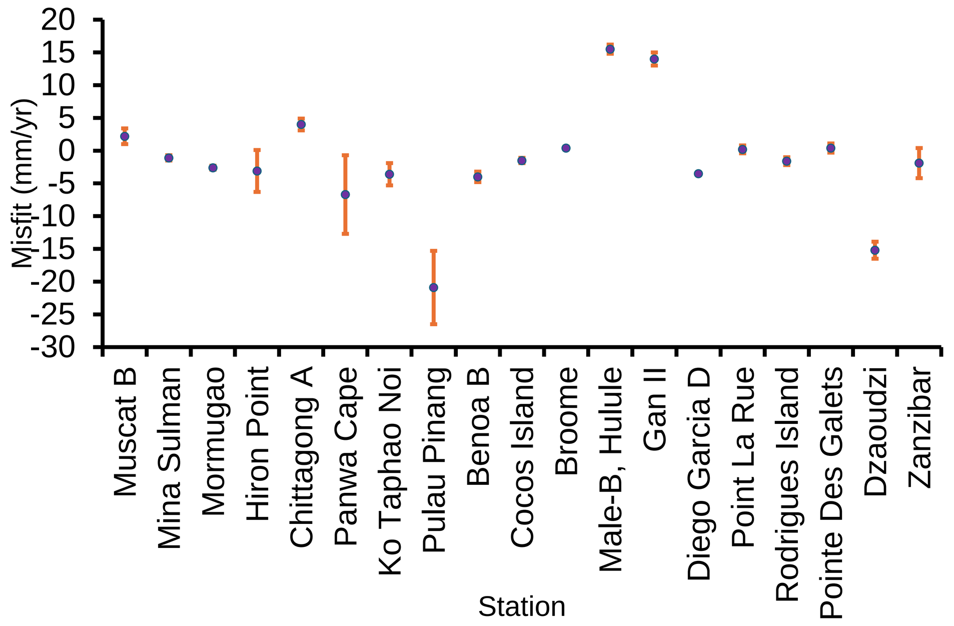

Figure 3: Linear misfits for all colocated sites.

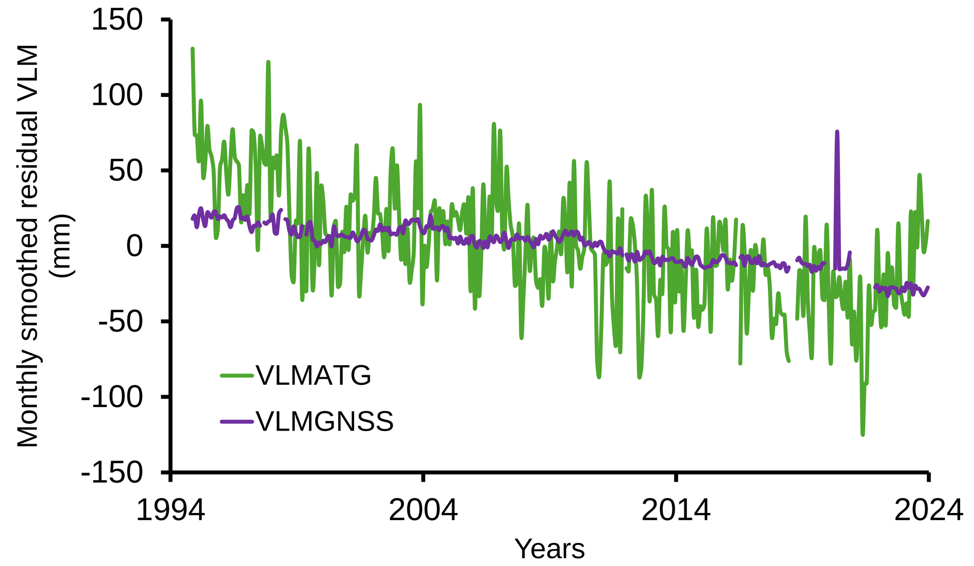

Figure 4: The corrected VLM record (ATG and GNSS) for Cocos Islands.

2. Evaluation of non-linear rates

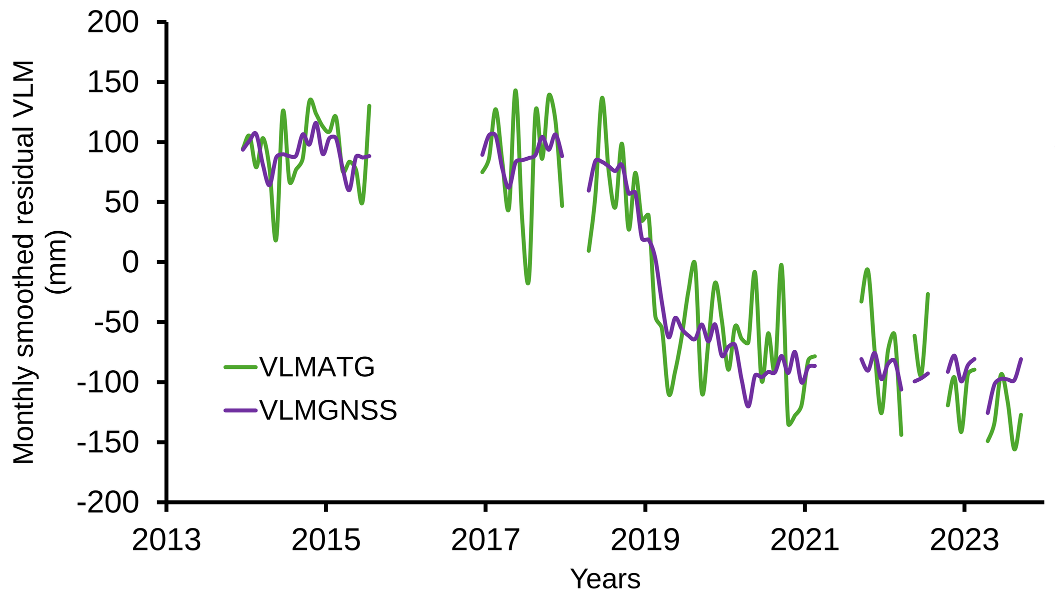

Figure 5: The corrected VLM record (ATG and GNSS) for Dzaoudzi.

- Dzaoudzi (MAYG; Figure 5) is a good example showing a clear non-linear signal.
- The record shows a shift in 2018 where a decrease in VLM is present in VLM_{ATG} confirmed by VLM_{GNSS}. Despite a low signal to noise ratio the VLM is observable unlike Coco Islands (Figure 4) suggesting local site-to-site factors are important.

3. Coexisting linear and non-linear signals

- Diego Garcia D (DGAR; Figure 6) exhibits evidence of both linear (VLM_{GNSS} record) and non-linear (VLM_{ATG} record) behaviour.
- The VLM_{ATG} contains a much lower signal to noise ratio compared with VLM_{GNSS}.
- Sites which are out of phase (e.g. Muscat; Figure 1) exhibit a ~2-month lag between A and TG, creating an oscillatory residual and a systematic bias in the VLM_{ATG}.
- The lag can be attributed to local ocean-climate dynamics (e.g. delayed ocean response to warming)[13]. Ref., 13 also identifies a 2-month delay at Rodrigues Island (Figure 1) and attributes it to westward advection and propagation (e.g. ENSO/IOD).

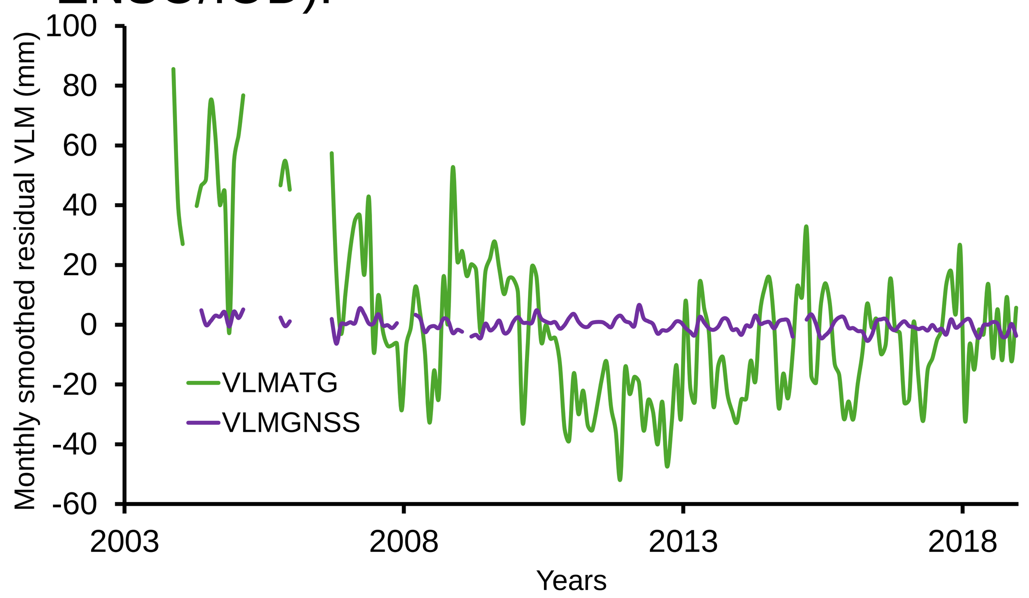

Figure 6: The corrected VLM record (ATG and GNSS) for Diego Garcia D.

Discussion:

Spatial extension across IO

We apply the linear method to 105 TGs across the IO and find high variability in the rates with uncertainty mostly less than 1.0 mm/yr (Figure 7). The spread of uncertainty for non-colocated and colocated sites is consistent suggesting the approach is applicable for IO.

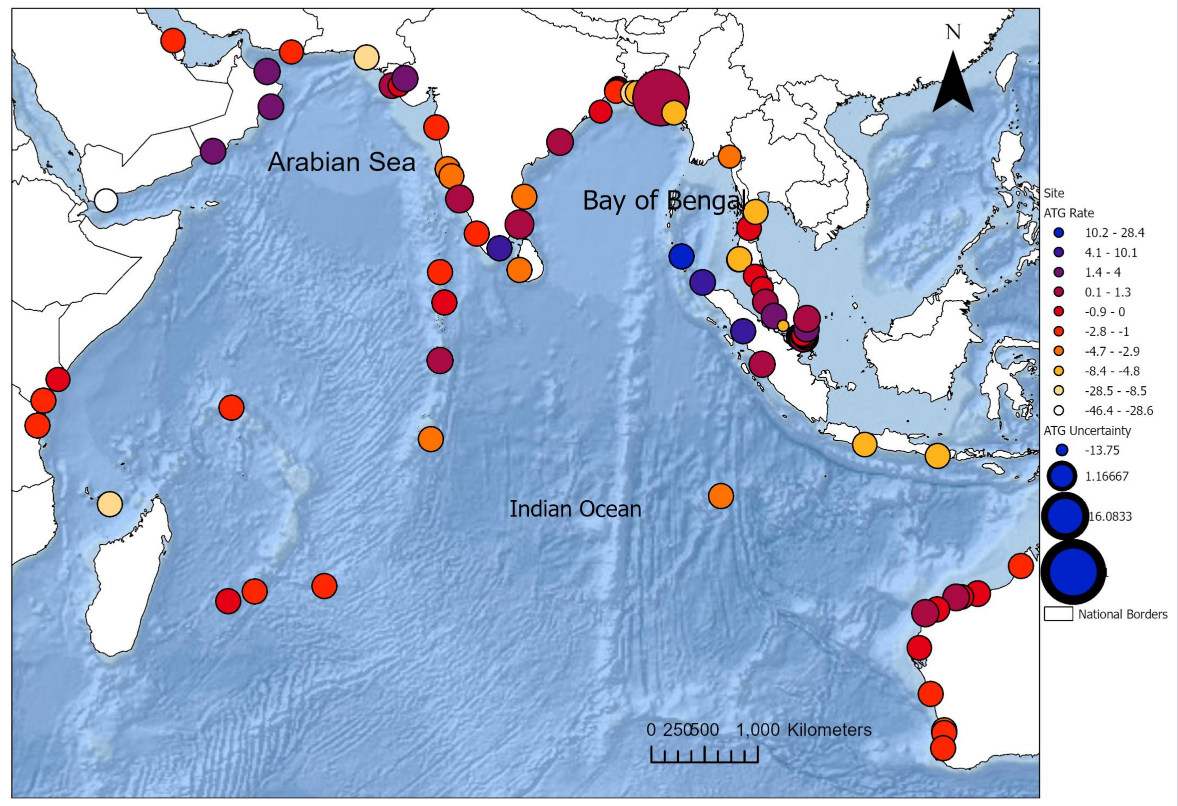

Figure 7: Linear rates and uncertainty for all sites across the IO.

- Aden (Yemen) and Tanjung Keling (Malaysia) exhibit the largest uncertainties while Tuticorin (India) has the lowest uncertainty.
- Our findings are consistent with other research[8,11] though with lower uncertainties in the Bay of Bengal.

Implications

The implications of our findings suggest that the methodology is robust, therefore it is possible to apply it to locations outside the IO. However, sensitivity testing using alternative denoising strategies is needed (e.g., Common Modes[14]). For sites without a colocated station, we demonstrate that the methodology is still feasible with limited data. Comparison with VLM_{GNSS} data enhances linear rate estimates by assessing the similarity between observed rates.

Conclusions and Next Steps:

We conclude that the methodology outlined can be successfully used to determine linear and characterise non-linear VLM across the IO, even for sites without colocated stations. Evaluation of non-linear rates reveals that the methodology can also be applied to sites which experience large non-linear VLM events (e.g. Figure 5).

Next step: Time series modelling is required to further characterise non-linear VLM, which could then be combined with linear contributions (in a stochastic forecasting model) to revise projections at individual locations (Figure 8).

The outputs from this analysis will then be used to inform local and regional scaler policy adaptation frameworks around the IO.

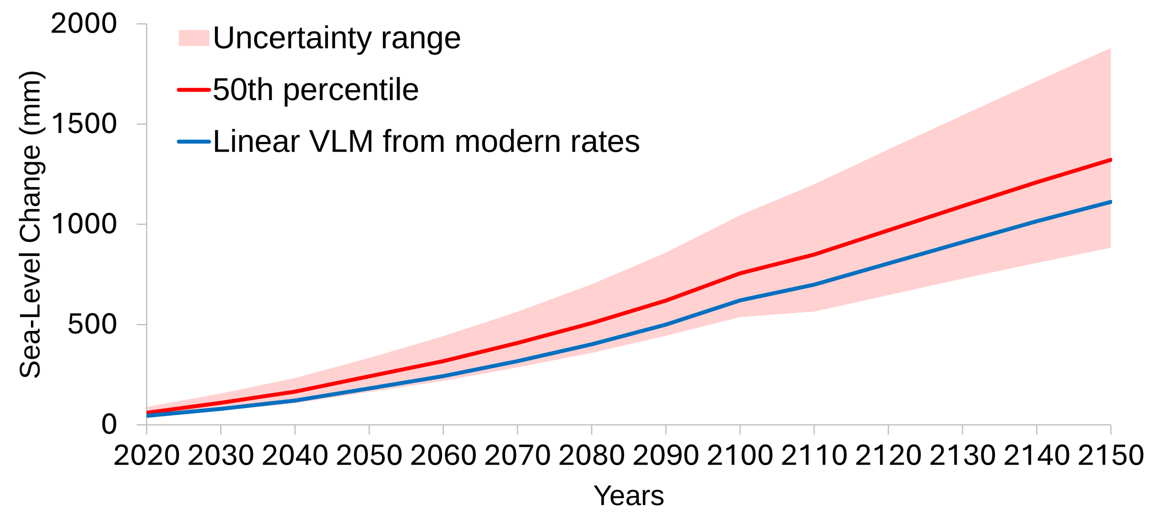

Figure 8: NASA[15] projection for Dzaoudzi (MAYG) to 2150 and with linear VLM based on modern rates (based on Figure 5).

References:

1. Wöppelmann, G. and Marcos, M., 2016. Reviews of Geophysics, 54(1), pp.64-92.
2. Haodong, L.I.U et al., 2024. Acta Geodynamica et Geomaterialia, 21(4)
3. Sreeraj, P. et al., 2022. Environmental Research Letters, 17(11), p.114016.
4. Shirzaei, M et al., 2021. Nature Reviews Earth & Environment, 2(1), pp.40-58.
5. Amin, M.K. and Hasan, G.J., 2025. Journal of Coastal Research, 113(SI), pp.215-219.
6. Horton, B.P et al., 2018. Annual Review of Environment and Resources, 43, pp.481-521.
7. Cazenave, A. and Moreira, L., 2022. Proceedings of the Royal Society A, 478(2261), p.20220049.
8. Oelsmann, J., 2024. Nature Geoscience, 17(2), pp.137-144.
9. Permanent Service for Mean Sea Level: https://psmsl.org/
10. Nevada Geodetic Laboratory, MAGNET Network: https://geodesy.unr.edu/
11. Martínez-Asensio, A. et al., 2019. *Global and Planetary Change*, *176*, pp.132-143.
12. NASA Jet Propulsion Laboratory (JPL): https://sealevel.nasa.gov/
13. Church, J.A. et al., 2006. *Global and Planetary Change*, *53*(3), pp.155-168.
14. Mazzotti, S. et al., 2008. *Journal of Geophysical Research: Oceans*, *113*(C11).
15. NASA Sea Level Projection Tool: https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool