Coastal inundation observations, trends and projections for Vanuatu

EXPLAINER

KLAEMET SAVE
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SPREP
Secretariat of the Pacific Regional Environment Programme

GREEN CLIMATE FUND

This publication should be cited as:

CSIRO. Coastal inundation observations, trends and projections for Vanuatu. A report to the Van-KIRAP project. Commonwealth Scientific and Industrial Research Organisation (CSIRO) Technical Report, Melbourne, Australia.

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The project team would like to acknowledge Sara Ortega Van Vloten (University of Cantabria) for close collaboration on production of modelling output, and Kevin Hennessy (Climate Comms) and Geoff Gooley (CSIRO) for providing helpful comments.

The project team would like to acknowledge Raviky Talae and Rebecca Gregory for images used on the front cover.

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Introduction

The risk of coastal inundation is due to a combination of factors, including tides, storm surges, storm waves, interannual sea level variability, and sea level rise. These factors are variously influenced in Vanuatu by natural climate variability, extremes, and change. One of the main contributors to sea level variability on seasonal to interannual timescales is the El Niño Southern Oscillation (ENSO). Sea level has risen due to climate change by 10–15 cm between 1993 and 2020 over the western tropical Pacific [1], which is faster than in the central and eastern parts of the tropical Pacific. This has consequences for Vanuatu in low-lying coastal areas that are most vulnerable to flooding and erosion, particularly in the immediate vicinity of natural resources, local communities and related infrastructure and commerce/trade.

Mean sea level is projected to rise due to climate change by about 0.13 m by 2030 compared to a baseline centred on 1995. By 2050, the rise is 0.23 m for a low greenhouse gas emissions pathway (RCP2.6) and 0.28 m for a high emissions pathway (RCP8.5). By 2090, the rise is 0.42 m for low emissions and 0.73 m for high emissions. Mean sea level rise must be combined with information about tides, storm surges, storm waves and interannual sea level variability to estimate extreme sea level events over multi-decadal (climate change) timescales.

The Van-KIRAP project has developed a national numerical ocean hazard modelling system to provide improved historic analyses and future projections of extreme sea level events for Vanuatu. Extreme sea level magnitudes have been calculated for events with average return periods of 10 years, 50 years and 100 years, for 20-year periods centred on 2030, 2050, 2070 and 2090, for various emissions pathways. For example, events with a 10-year return period are typically around 0.8–1.0 m for the baseline period and 1.1–1.3 m by 2050 for a high emissions pathway. The **Vanuatu Climate Futures portal** has a coastal inundation mapping tool that enables visualisation of areas and assets that may be inundated. The combination of such 'Climate Information Service' (CIS) products is intended to provide science-based evidence to inform hazard-based impact and integrated risk assessments as part of national climate change policy development, sector-specific adaptation planning and climate-related disaster risk management.

The purpose of this Van-KIRAP 'explainer' is to provide a convenient, 'non-technical' summary of the key scientific concepts, terms, definitions, methods, analytics and potential applications related to the science of coastal inundation. This is to assist capacity development of sectoral policy-makers, planners and related CIS intermediaries (purveyors) including the VMGD, consultancies, NGOs, Community Climate Change Centres etc.

Observations and trends

Sea level

One of the most pressing climate change concerns is the rise in sea levels resulting from global warming. While this is a long-term global effect, there are regional and to some extent more local differences at national scale. The sea level rise observed over the western tropical Pacific is about 10–15 cm on average between 1993 and 2020 [1], which is faster than in the central and eastern parts of the tropical Pacific [2] (Figure 1). This has consequences for Vanuatu in low-lying coastal areas that are most vulnerable to flooding and erosion; in particular, immediately adjacent to local communities, natural resources, built assets and commerce/trade. Vertical land motion, due to earthquakes, isostatic adjustment, compaction of sediments and other processes may influence local relative sea level [3] and can sometimes explain differences in long-term sea level trends between tide gauges and satellite altimetry (see Appendix A: Vertical Land Movement). It should be noted that one of the main contributors to natural sea level variability on seasonal to interannual timescales is ENSO (see Climate variability factsheet).

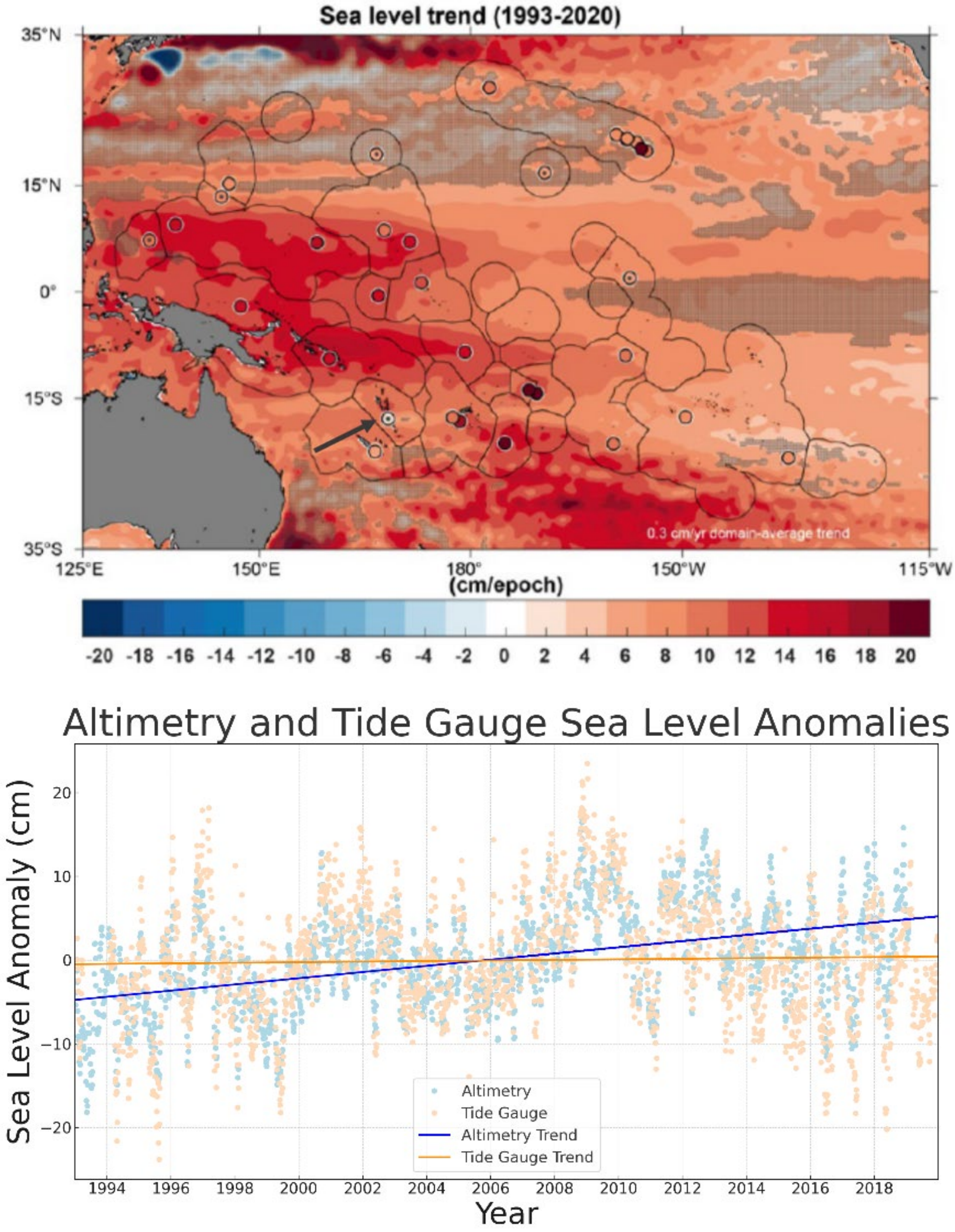

Figure 1 Top: Sea surface height (SSH) trends (cm/epoch) from satellite altimetry (shaded contours) and sea level trends from tide gauges (circles) during 1993–2020. Trends that are less than interannual variability, which is determined by the standard deviation of monthly anomalies, are indicated by hatching and circles with dots for the altimetry and tide gauges, respectively. An arrow points to Port Vila in Vanuatu. Source: [1] Bottom: Daily data of satellite altimetry measured SSH and the tide gauge measured relative sea level see Sea Level Explorer Tool (https://ccar.colorado.edu/altimetry/).

Extreme sea level and coastal inundation

The previous section of this document describes long-term trends in sea level associated with climate change at a regional scale. At a finer spatial scale, any given coastal location's risk of being inundated at any given time is due to a combination of factors, including tides, storm surges, storm waves and interannual sea level variability (due to climate variability such as ENSO). Local geomorphology influences the relative contributions of these different factors and how they combine to create extreme sea levels. For example, coastal bathymetry (shape of the sea-bed), especially the presence of offshore reefs, influence storm surges and wave-driven contributions. Offshore reefs cause waves to break offshore and thereby reduce the wave energy (and height) of the waves that eventually reach the coast. Steep shorelines (both with and without reefs) and greater offshore depths allow higher storm waves to reach the coast but are also less prone to the wind-driven components of storm surge (Figure 2).

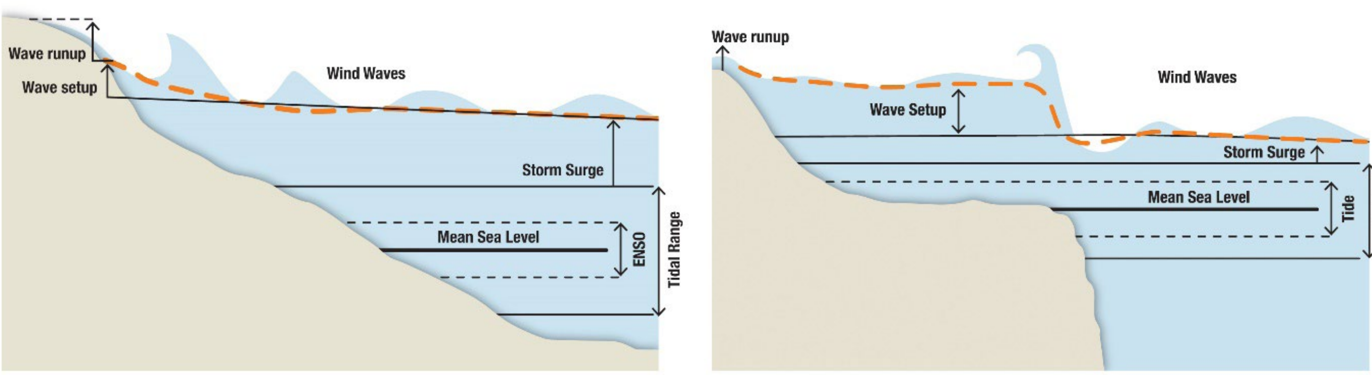

Figure 2 Schematic of the contributions of extreme sea levels at the coast for (a) a typical continental coastline and (b) for a reef fronted island.

The different contributions of tides, storm surge, storm waves and interannual sea level variability, and how they can combine to produce extreme sea levels, can be seen in total water level observations at Luganville and Port Vila (Figure 3a and 3c). These hourly water levels have been processed to separate tides due to the sun and moon (astronomical tides) from short-term non-tidal fluctuations (from storm tides and storm waves) and long-term changes (due to sea level variability and sea level rise). Extreme sea levels are rare and may not always occur due to a tropical cyclone; for instance, if a storm surge happens at low tide, the total water level may not be extreme at the adjacent coastline.

Extreme value analysis (EVA) is a statistical method used to assess and characterise extreme events that have a low probability of occurring but can have significant consequences such as impacts on critical infrastructure, amenity of local communities, commerce/trade and environmental resources such as protective shorelines, seagrass beds, mangroves, inshore reef structure etc. The average return period (also known as the average recurrence interval, ARI) is an EVA measure used to describe the average time between occurrences of an event of a certain magnitude (typically associated with known/ expected impacts). It helps in quantifying the likelihood of an event happening within a given time frame. For example, a 50-year return period flood means that, on average, a flood of that magnitude is expected to occur once every 50 years.

Figure 3b and 3d show the return period curve resulting from the EVA applied to the extreme water levels observed at the Luganville and Port Vila tide gauges. In this figure, the black dots represent the 'empirical' return periods at the tide gauges, the red lines are the statistical (generalised Pareto distribution fitted) return period prediction and the blue area represents the uncertainty of the prediction. Figure 3c and 3d show that although Tropical Cyclone Pam had the highest (short term) storm surge sea level on record, it was not the highest observed total water level; that event occurred in 2008 and was a combination of a very high spring tide and a high interannual (or long-term) sea level. Such natural events are sometimes called 'King Tides'.

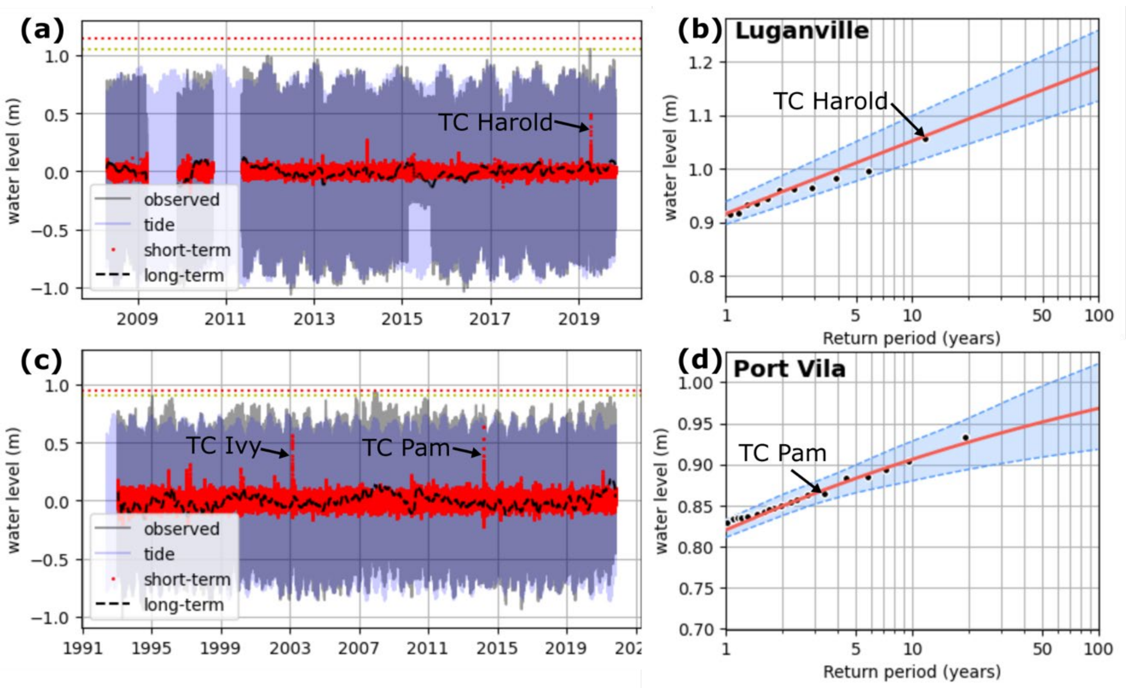

Figure 3: (a) hourly water levels from the Luganville tide gauge; (b) extreme value analysis return periods based on the Luganville tide gauge water levels; (c) hourly water levels from the Port Vila tide gauge; (d) return periods based on the Port Vila tide gauge water levels. In subplots a and c, the 10-year and 50-year return intervals are indicated with horizontal yellow and red dotted lines respectively. In subplots b and d, the black dots represent the "empirical" return periods; the red lines and blue bands are the statistical fit and associated uncertainty (95 % confidence limits) of the return periods.

While tide gauge observations and associated return periods can be valuable for planning and risk assessment purposes, tide gauges are usually located in very sheltered harbours and extreme sea levels they observe are typically relevant only in the immediate area around the harbour. Pacific islands like Vanuatu tend to have relatively high exposure to storm wave setup and runup, with relatively high local variability [4], [5]. In practice severe inundation may occur in exposed areas, while tide gauges located sometimes only a short distance away (on the same island) do not record particularly extreme sea levels [6], [7]. The storm surge from Cyclone Pam measured at the Port Vila tide gauge is an example of this. The total water level recorded at the tide gauge was minor compared to the catastrophic inundation and erosion that occurred a few kilometres along the east coast of Efate Island [8]. An indication of the severity of the coastal impact can be found using the CAWCR Wave Hindcast [9], [10]; it shows that wave heights off the south-east coast of Efate were by far the largest in the hindcast's entire 40+ year record (Figure 4). The EVA return periods for the CAWCR wave heights near Luganville and Port Vila show something else: with extreme storm waves associated with cyclones occurring only a few times during the 40+ year record; wave heights during Cyclone Pam are so much higher than any other event in the hindcast record that it falls outside the confidence limits of the EVA imposed by the rest of the data. This relative rarity of extremes in the historical record translates into very high uncertainty in the EVA estimates (indicated in blue bands in Figure 4b and 4d). For instance, the uncertainty in the 100-year return wave height is between ~5 and ~12 m.

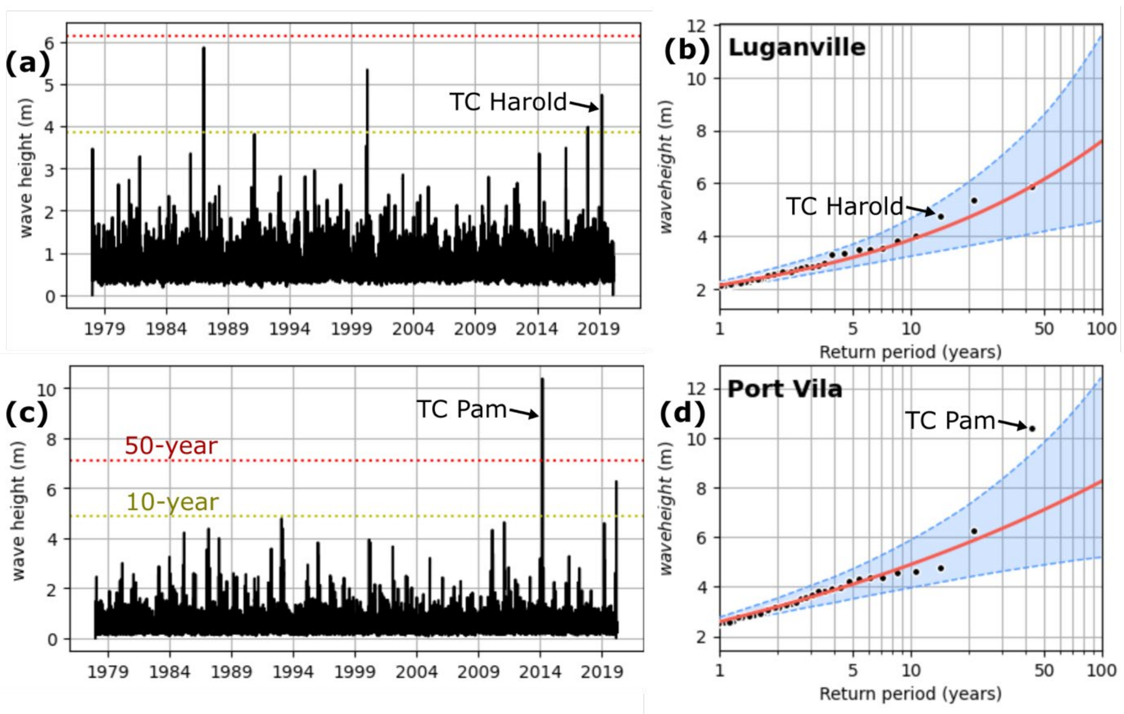

Figure 4: (a) hourly (significant) wave heights from the CAWCR Wave Hindcast offshore from the Luganville tide gauge location (east of Million Dollar Point); (b) extreme value analysis return periods based on the Luganville wave data; (c) hourly water levels from the Port Vila tide gauge; (d) return periods based on the Port Vila tide gauge water levels. In subplots b and d, the black dots represent the "empirical" return periods; the red lines and blue bands are the statistical fit and associated uncertainty (95 % confidence limits) of the return periods.

In summary, the small number of long-term tide gauge records (currently only two: Port Vila and Luganville) and the inability of tide gauges to record, and through analysis of historical records predict the frequency of extreme sea levels, experienced in some cases just a short distance away, means most locations in Vanuatu cannot rely on tide gauges alone to provide adequate coastal inundation risk information. While historical global wave hindcasts (like the CAWCR Hindcast) can provide more information, their resolution is too coarse to resolve local exposure, and EVA of the relatively rare extreme TC/storm waves is highly uncertain. To address this in the Van-KIRAP project, a national-scale numerical ocean hazard modelling system has been built to provide improved historic analyses and future projections of extreme sea levels for Vanuatu. This and related sea level rise projections are discussed in the next section.

Ocean hazard modelling and sea level rise projections

Sea level rise projections

The sea level rise (SLR) projections used within the Van-KIRAP project are the 'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for Vanuatu[1] [11]. The NextGen SLR projections for Vanuatu show a median rise of about 0.13 m by 2030 (Table 1) compared to a baseline of 1995 (1986–2005). By 2050, the rise is 0.23 m for low emissions (RCP2.6) and 0.28 m for high emissions (RCP8.5; also see Appendix D). By 2090, the rise is 0.42 m for low emissions and 0.73 m for high emissions (Table 1 and Figure 4). Vertical land motion is not included and may affect overall changes (see Climate variability explainer).

Table 1 Median sea level projections for Vanuatu with 5–95 % uncertainty range relative to 1986–2005 for RCPs 2.6, 4.5, and 8.5. Units are metres. Source: [11].

20-year periods centred on	RCP2.6		RCP4.5		RCP8.5	
2030	0.13	[0.10–0.17]	0.13	[0.09–0.17]	0.14	[0.10–0.18]
2050	0.23	[0.17–0.30]	0.24	[0.18–0.31]	0.28	[0.22–0.37]
2070	0.32	[0.24–0.43]	0.37	[0.28–0.48]	0.48	[0.37–0.64]
2090	0.42	[0.30–0.56]	0.50	[0.38–0.68]	0.73	[0.56–0.99]

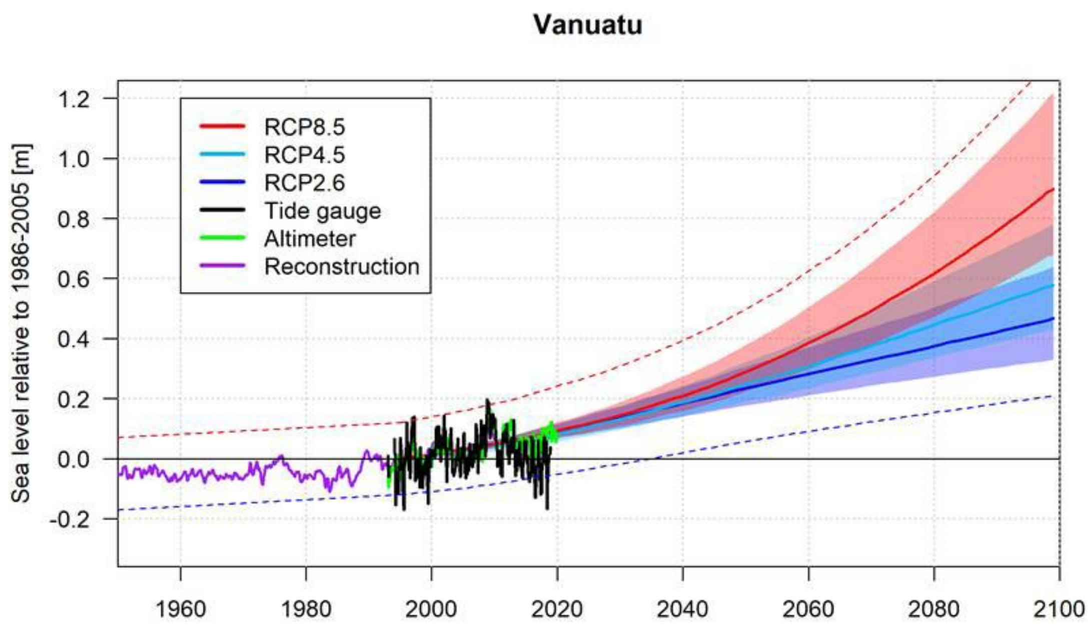

Figure 5 Timeseries of past and future sea level rise. Port Vila tide gauge records of relative sea level are indicated in black, the satellite record in green, reconstructed sea level data is shown in purple, all are monthly means and referenced to mean sea level between 1986–2005. Multi-model mean projections from 1995–2100 are given for three RCPs with the 5–95 % uncertainty range shown by the shaded regions. The dashed lines are an estimate of month-to-month variability in sea level (5–95 % uncertainty range about the projections and reconstruction) and indicate that individual monthly averages of sea level can be above or below longer-term averages.

[1] This is a reassessment of CMIP5-based sea level rise projections, which were published by the IPCC in 2019.

National-scale modelling of extreme sea levels and waves

The underpinning model used in the Van-KIRAP ocean hazard modelling system is called SCHISM-WWM3[2] [12] (see Appendix B: Coastal and ocean modelling: SCHISM-WWM3). It uses an unstructured mesh which can represent complex coastlines, islands and offshore reefs with high resolution at the coast and over reefs, and lower resolution in deep water. It simulates the combined effects of tides, storm surge, waves and background sea level. Data from the Port Vila and Luganville tide gauges as well as wave data from satellites and the Van-KIRAP ocean buoys were used to 'tune' and assess the modelling system (see Appendix C). The Van-KIRAP ocean hazard modelling system has been run in two modes: (1) historic mode and (2) probabilistic (future climate) scenario mode. These are described in more detail in the following sub-sections.

- Historic mode produced hourly data output for a 40-year period (1980–2020) that accounted for tides, waves, storm surge and background sea level variability and rise. Using the same EVA method discussed in the previous section, return periods were calculated from these outputs.
- Probabilistic scenario mode was used to better account for statistically rare, but high-impact tropical cyclones (TCs). Complex techniques were used whereby thousands of "synthetic" TCs generated using advanced TC modelling were reduced to a subset of 1000 using cluster analysis, which reduces the overall number while still representing the full spread of possible tracks and intensities. This population of 1000 TCs were then modelled using the coastal ocean model. The resulting extreme sea levels were then combined with scenarios based on future projections of sea level rise and the historic extremes to provide an indicator of future impacts of climate change (see the Tropical cyclone explainer). A long (~1000-year) synthetic timeseries was then constructed from predicted tides, sea level variability and sea level rise, and combined with the storm surge and storm waves from the synthetic TC simulations in the Van-KIRAP ocean hazard modelling system. A similar EVA analysis as described for the historic mode was then performed, to produce return periods for extreme sea levels and storm waves into the future.

The historic mode and probabilistic scenario mode were run assuming 'baseline' historic sea level variability with mean sea level at zero between 1990 and 1995 (a period of relatively low ENSO variability); the future sea level rise scenarios outlined in Table 1 were then convolved with the baseline period to provide future extreme sea level return periods. An example is shown schematically in Figure 6.

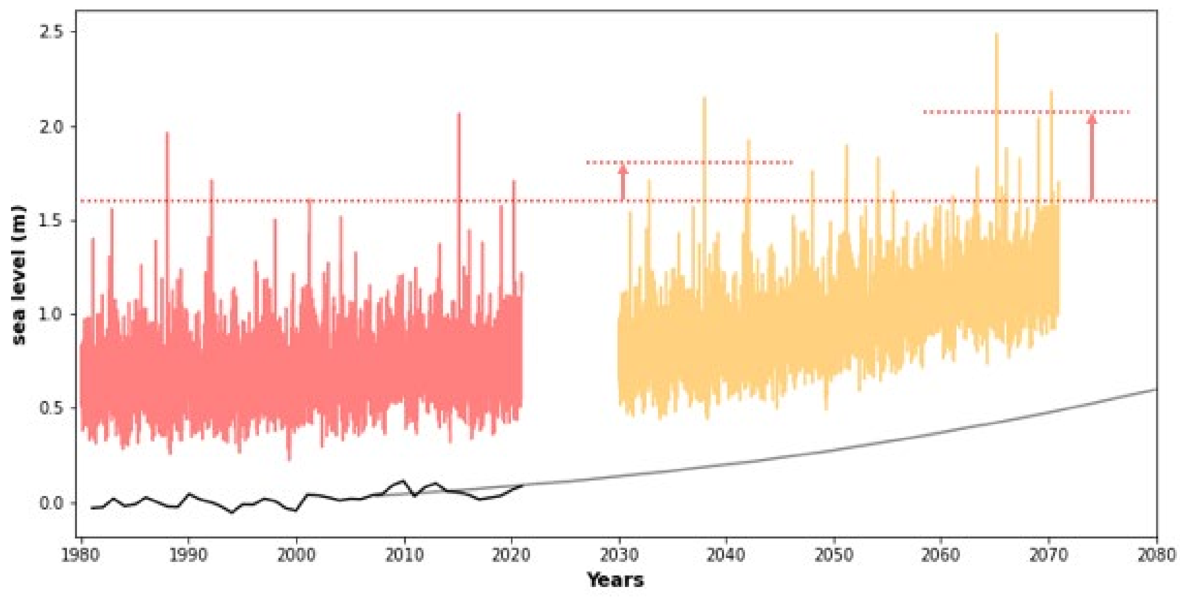

Figure 6 Historic (black line) and projected (median, RCP8.5, grey line) sea level for an example output point from the Van-KIRAP coastal hazard model. Daily maximum total water level is shown for current climate (pink lines) and projected climate (yellow line). The 10-year "storm tide" return period (or average recurrence interval; ARI) is shown for current climate (pink dotted line) with higher values for future climate shown (up-arrows).

[2] SCHISM: Semi-implicit Cross-scale Hydroscience Integrated System Model

Thus, these extreme sea level projections are estimated for baseline conditions and future conditions (RCP2.6, RCP4.5 and RCP8.5 emissions scenarios) and include information about tides, waves, storm surges, annual sea level variability and sea level rise. Extreme sea level magnitudes have been calculated for events with average return periods of 10-, 50- and 100-years for 20-year periods centred on 2030, 2050, 2070 and 2090, for various emissions pathways (see Appendix E: ARIs for Vanuatu). Table 2 gives baseline, 2050 and 2090 return periods (ARIs) for locations from North to South Vanuatu for the RCP8.5 emissions pathway. For example, events with a 10-year return period are typically around 0.8–1.0 m for the baseline period and 1.1–1.3 m by 2050 for a high emissions pathway.

These extreme sea level return periods are available on the Vanuatu Climate Futures portal for 2 km spacings along the Vanuatu coast (2377 points in total; see Figure 7 for an example), and as gridded outputs (on the native computation mesh) across the entire model domain.

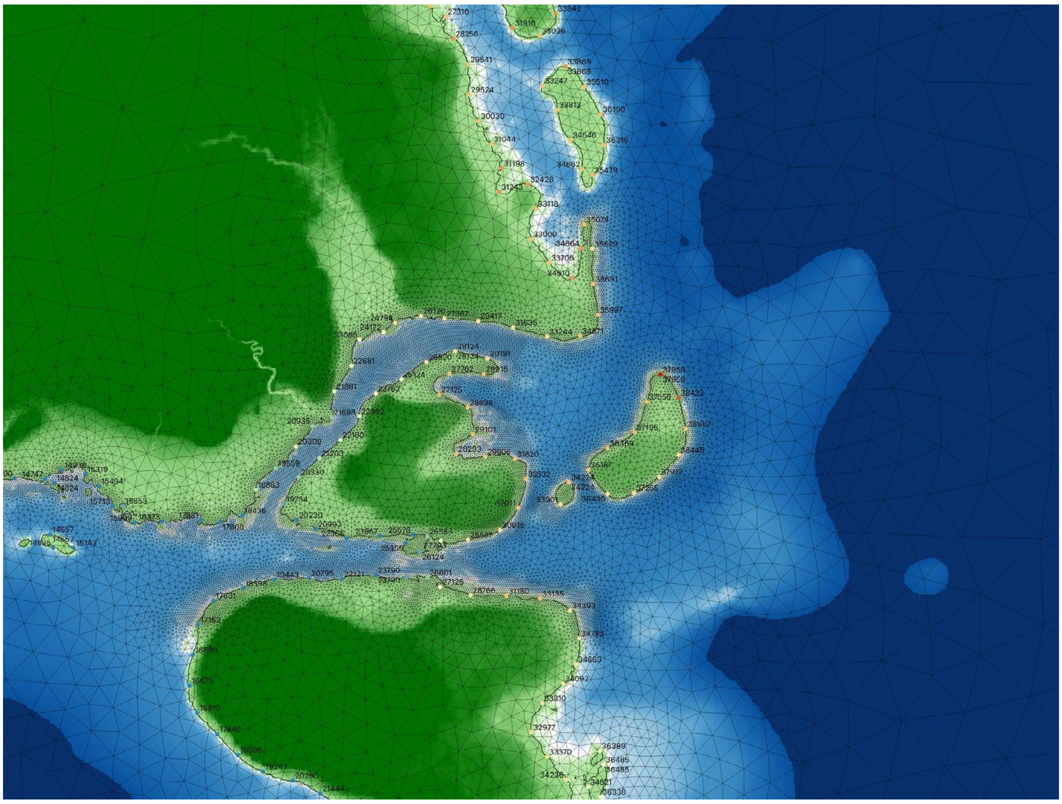

Figure 7: An illustration of the coastal ocean model mesh and the coastal points where extreme sea levels and average recurrence intervals are provided. The red X's indicate the regular coastal points, the orange dots indicate the nearest 'wet' computational node and the black numbers are the node index within the entire computational mesh.

Table 2 Mean value for extreme sea level intensity (m) for a 40-year baseline centred on 2000 and future 20-year periods centred on 2050 and 2090 with average recurrence intervals (ARIs) of 10-years, 50-years and 100-years for selected sites in Vanuatu for RCP8.5 (see Vanuatu Climate Futures portal *for more data points, and RCP2.6 and RCP4.5 emission scenarios. Node # corresponds with these data sets).*

Location	Node #	baseline			2050			2090		
		10-yr ARI	50-yr ARI	100-yr ARI	10-yr ARI	50-yr ARI	100-yr ARI	10-yr ARI	50-yr ARI	100-yr ARI
Sola	46201	1.06	1.12	1.15	1.34	1.40	1.43	1.81	1.86	1.89
Hog Harbour	18632	1.03	1.09	1.12	1.31	1.37	1.40	1.78	1.84	1.86
Lamap	51686	0.96	1.03	1.05	1.24	1.31	1.33	1.71	1.77	1.79
Port Vila	71667	0.86	0.92	0.95	1.14	1.20	1.23	1.60	1.66	1.69
Lenakel	92863	0.87	0.98	1.04	1.15	1.26	1.32	1.61	1.72	1.79
Aneghowhat	97735	1.01	1.24	1.38	1.29	1.52	1.66	1.75	1.98	2.12

Coastal inundation visualisation on the Vanuatu Climate Futures portal

When combined with a map of buildings and critical infrastructure such as roads, bridges and other public amenities (e.g. airports, hospitals, schools, evacuation centres etc.), this information can highlight exposed and vulnerable assets that are potentially impacted by coastal inundation (see Coastal inundation of roads infobyte). The extreme sea level return periods described in the last section were used to calculate inundation exposure, which can be visualised in the Vanuatu Climate Futures portal wherever high-resolution topographic LiDAR survey data are available. LiDAR data are currently available for large areas of Espiritu Santo, Malekula and Efate (see the PACCSAP LiDAR Factsheet for detailed description); although more LiDAR survey data are becoming available (see LiDAR factsheet). An example is given in Figure 8.

Figure 8: Example of visualisation of coastal inundation for 10-, 50-, and 100-year return levels near the Sarakata River, Luganville. Explore this and more data in the Vanuatu Climate Futures portal.

The scientific modelling and analysis of coastal inundation impacts at fine spatial scales is technically complex, with known limitations on the relevant methodologies and utility of the data. It is also the case that such applications, within these known limitations, are highly valuable for undertaking fit-for-purpose analytics and generating tailored metrics as an evidence basis for risk assessments, adaptation planning and associated decision-making. The Van-KIRAP project has developed these capabilities in the form of robust, science-based Climate Information Services for Vanuatu, all designed to help facilitate resilient development over multi-decadal (climate change) timescales.

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Appendix A: Vertical land movement

The annual number of high sea level events for the tropical Pacific islands with long-term tide gauge measurements[3] (Figure 6) show Port Vila tide gauge's trend changing since 2008 due to vertical uplift of the land [3]. The rapid increase in the frequency of coastal flooding days in Pago Pago, American Samoa, is an example of how vertical land subsidence exacerbates risks associated with the global sea level rise trend caused by greenhouse warming [3], [13]. Note that the satellite-measured sea level trends for Pago Pago and Port Vila are similar (about 6 cm of sea level rise since 1993; Figure 1).

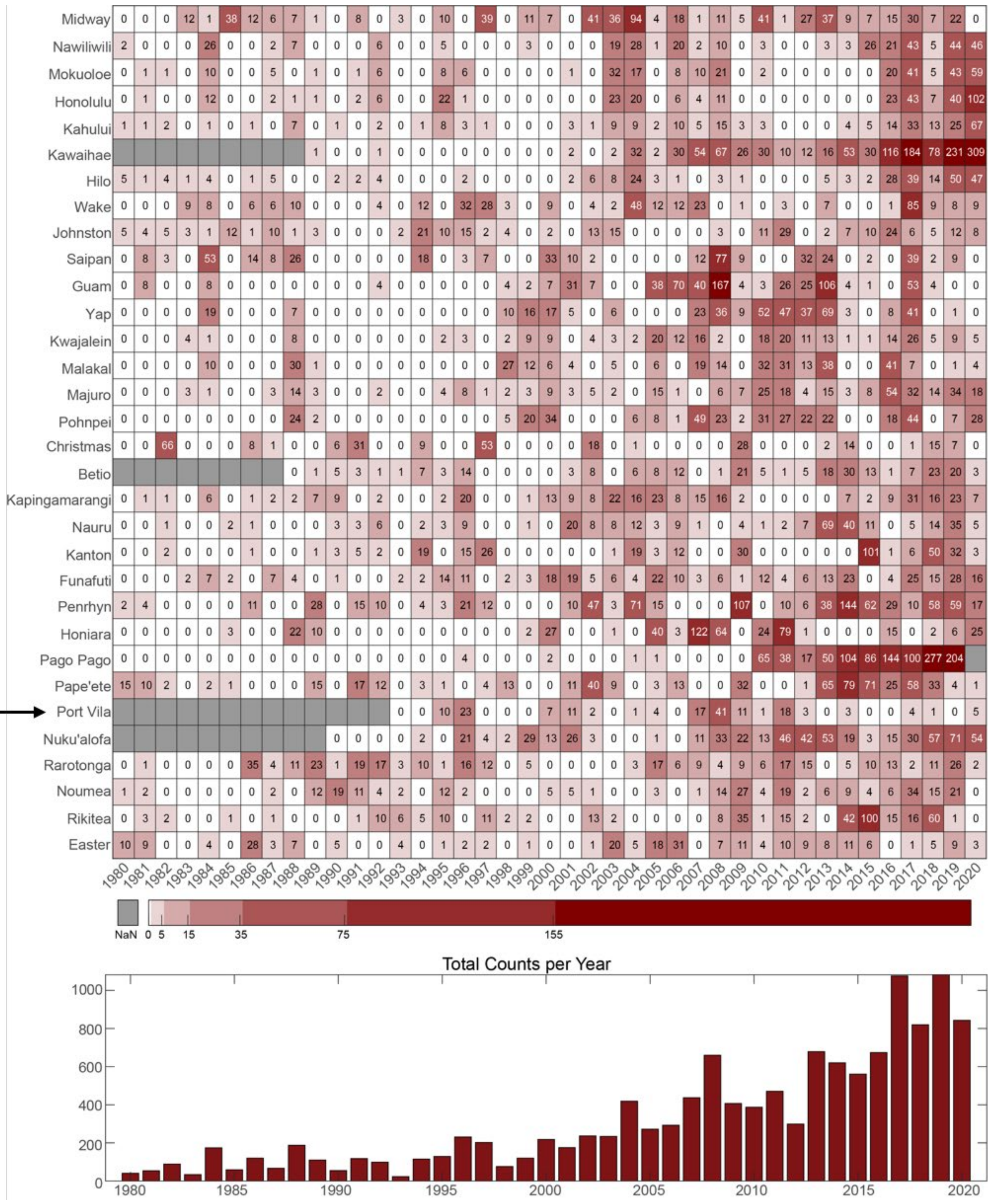

Figure 9 Minor flood frequency from tide gauges in the tropical Pacific. The top plot shows the total number of minor flood days per year for 1980–2020. An arrow points to Port Vila in Vanuatu. The bottom plot shows the annual total number of minor flood counts for all stations combined. Adapted from [1] to include Port Vila.

[3] Note that the Port Vila tide gauge record was not shown in the PCCM report because there were no observations prior to 1993.

Appendix B: Coastal ocean modelling: SCHISM-WWM3

With any coastal ocean modelling, there is a large workload associated with setting up the model before any simulations can take place. This includes (1) obtaining good quality input data sets such as the bathymetry and coastline, (2) creating the model mesh and ensuring mesh resolution is prescribed appropriately to enable the model to simulate processes nearshore and around features such as reefs, (3) identifying suitable data sets to 'force' the model on the outer boundary in terms of water levels (elevation), current velocities, and tidal components, and extracting/converting the data into the required model format, (4) identifying and formatting appropriate atmospheric (wind and mean sea level pressure) forcing data sets, (5) creating spatial maps of bottom friction associated with different seabed habitats and topographies, (6) identifying appropriate observation data against which to calibrate and validate model outputs, and (7) conducting test simulations and checking the outputs against observational data, and recalibrating the model where required. Once these steps have been completed, simulations can be run for different storm events and scenarios (e.g. sea level rise) to investigate coastal hazards such as inundation.

The SCHISM-WWM3 coastal ocean model is composed of a hydrodynamic model and a wave model that are two-way coupled (pass critical information to each other as the models perform their simulations) so they can account for non-linear current-wave interactions in the dynamic nearshore coastal zone. There are several other advantages in using SCHISM-WWM3:

- It runs on an unstructured mesh (Figure 10) made up of triangular elements, which means it is very good at accurately representing complex coastlines and channels.
- High mesh resolution (small elements) can be easily placed in areas of complex bathymetry, which the model needs to resolve the processes accurately, whereas this is much more difficult using structured (rectilinear or curvilinear) ocean models that often require nesting multiple model domains to achieve the required resolution transition.
- SCHISM-WWM3 is widely used by the international scientific community and industry. It is the model of choice for operational forecast systems in many countries (e.g., Central Weather Bureau of Taiwan; California Dept. of Water Resources; National Laboratory of Civil Engineering, Portugal) meaning it has been well tested and proven to be very reliable and accurate.

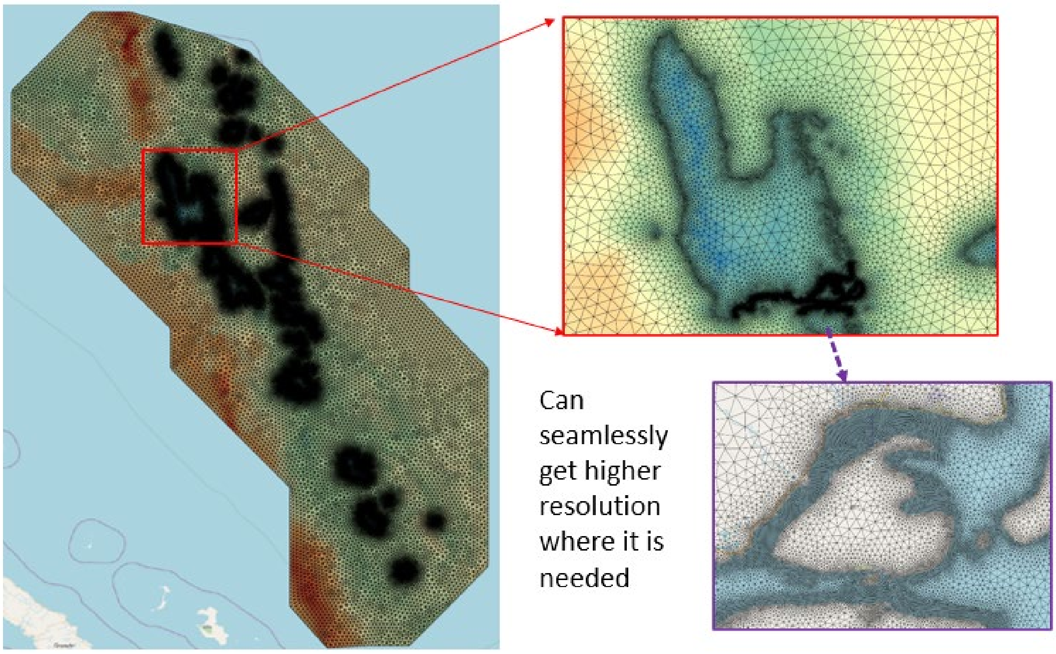

Figure 10 Domain for unstructured mesh model (left) and examples of the mesh at higher resolution showing seamless transitions at higher resolutions.

A key requirement for SCHISM high-quality model simulations is accurate and high-resolution bathymetry. Obtaining realistic simulations of coastal ocean and nearshore processes using a numerical modelling approach is highly reliant on using accurate bathymetric data at sufficiently high resolution (Figure 11).

While GEBCO data were not high enough resolution for Van-KIRAP coastal modelling, revised EOMAP (https://www.eomap.com/) data [14] informed by PACCSAP-funded Vanuatu LiDAR data (https://www.pacificclimatechange.net/sites/default/files/LiDAR-Vanuatu) was produced. This was critically important to obtaining realistic coastal inundation simulations. These data will also be of value to numerous other sector interests within the project (e.g. fisheries, tourism), as well as representing an important resource for Vanuatu government agencies.

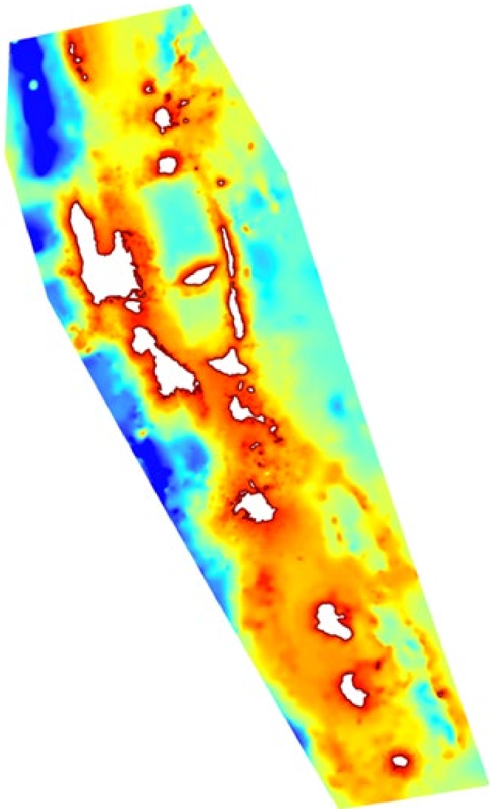

Figure 11 High-resolution satellite-derived bathymetry using revised EOMAP data, available for the entire Vanuatu archipelago.

Appendix C: Extreme sea level analysis

The hourly tide gauge records at Port Vila (from 1993 to 2021) and at Luganville (from 2008 to 2021) were sourced from the University of Hawai'i Sea Level Center (https://uhslc.soest.hawaii.edu/) and the Australian Bureau of Meteorology (James Chittleborough, Tidal Unit, personal communication), respectively. These hourly data sets were used for both calibration and verification of the Van-KIRAP ocean hazard modelling system and for analysis of extreme sea levels (for example, as presented in the Extreme Sea Level and Coastal inundation section). The data were compiled as follows:

Any vertical offsets (biases) in the water level data were removed by subtracting the mean sea level between 1990 and 1995, a period of relatively low sea level variability and associated ENSO extremes.

1. Predicted astronomical tide was computed using up to 28 harmonic constituents using the UTide software (https://pypi.org/project/UTide/).
2. The residual (bias corrected observed water level minus predicted tide) was then filtered using a 30-day median low pass filter. This low pass output contains the 'long-term' processes of sea level rise and interannual and seasonal fluctuations in sea level. The remainder (residual minus low pass) contains 'short-term' processes such as storm surge and wave setup.

The resulting residual sea levels isolate the contribution of short term (hourly to weekly) atmospheric forcing to extreme water levels. It is noted that ~40 years of deterministic data are not enough to reduce high uncertainties in probabilistic (risk-based) TC storm wave heights.

The IBTRACs [15] data set was then used to identify when a TC was located within a 3 nautical degree radius of the tide gauge. Annual maximum values were then associated within a 24-hour window of the TC passing. Table 3 presents the top ten atmospherically driven storm-surge water levels at Port Vila. TC Pam in March 2015 tops the list of storm-surge (0.6 m), followed by TC Ivy in May 2004 (0.54 m), and these stand out compared to the other events (less than 0.27 m). Noting here that the impact of these events on inundation will require further investigation on the coincidence of the atmospheric driven storm-surge with the phase of the tide and seasonal sea levels (e.g. ENSO).

Table 3 Storm surge water levels at Port Vila. Levels are relative to 30-day median sea level. TC events can be viewed online by appending the IBTRACS_SID to the end of the following web address http://ibtracs.unca.edu/index.php?name=v04r00- IBTRACS_SID , e.g. http://ibtracs.unca.edu/index.php?name=v04r00-2015066S08170

	Storm surge [m]	Date	IBTRACS_SID	Name
1	0.60	2015031401	2015066S08170	PAM2015
2	0.54	2004022617	2004052S15172	IVY2004
3	0.26	1994012705	NA	NA
4	0.26	1998032214	1998076S11170	YALI1998
5	0.25	2001030100	2001056S11163	PAULA2001
6	0.24	2019010109	NA	NA
7	0.22	1996122817	NA	NA
8	0.22	2003013022	NA	NA
9	0.21	1981021206	1981039S09178	CLIFF1981
10	0.20	2011011214	2011010S17169	VANIA2011

Appendix D: Sea level rise

Global climate models that produced climate projections for the Coupled Model Intercomparison Project (CMIP) Phase 5 and Phase 6 (CMIP5 and CMIP6 respectively) are incapable of simulating all the processes that contribute to sea level rise. They only simulate sea level variability due to ocean circulation changes at very coarse spatial scale ('dynamic sea level') and the thermosteric changes (ocean expansion due to heating). The contributions of the cryosphere (glaciers, ice caps, etc.), land water storage and global isostatic adjustment (GIA- movement of earth's crust due to loading/unloading of ice) are not accounted for in CMIP models [16] (Figure 12).

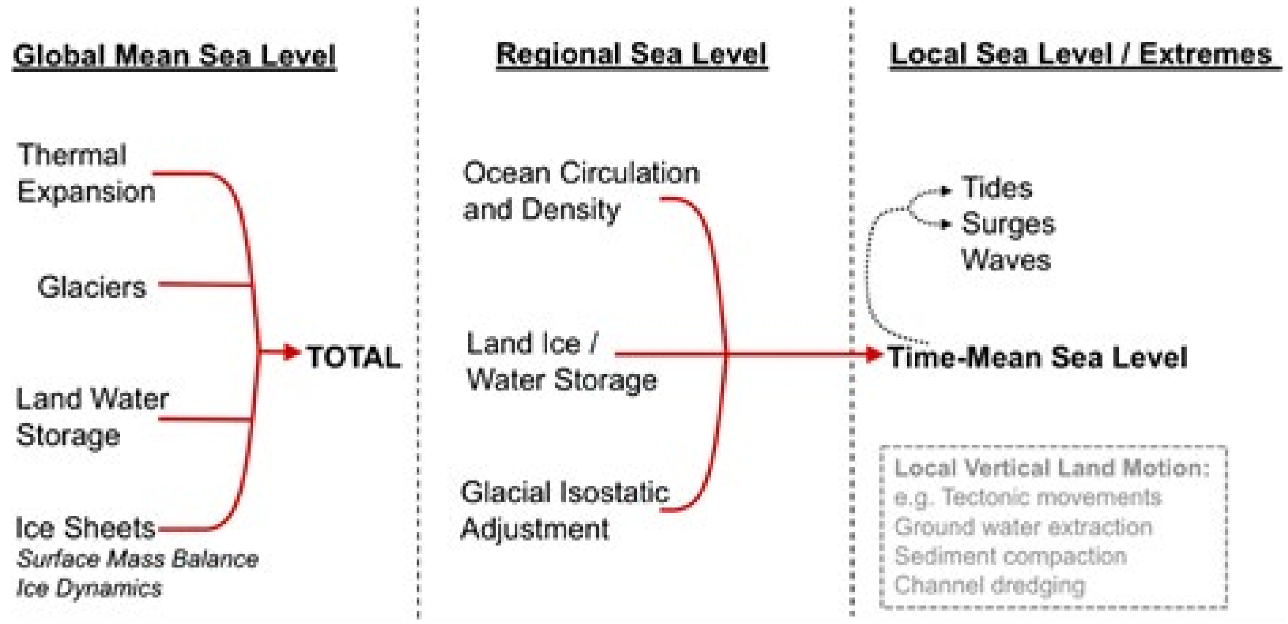

Figure 12 Components of global mean sea level (GMSL), regional sea level (RSL) and local sea level (LSL). Source: van de Wal et al. [16].

In future, the ice contributions and (locally) GIA become very important [16] (Figure 13), where proportional contributions to global SLR of different components change through time: thermal expansion (TE), glaciers (GL), the Greenland ice sheet (GIS), Antarctica (Ant) and land water storage changes (LWS) (GIA doesn't change global mean sea level, but makes for relatively large regional differences). The dotted blue line indicates the increase in the dynamic contribution of the Antarctic ice sheet if marine-based sectors of Antarctica collapse – this remains a major unknown on the upper bound of sea level rise.

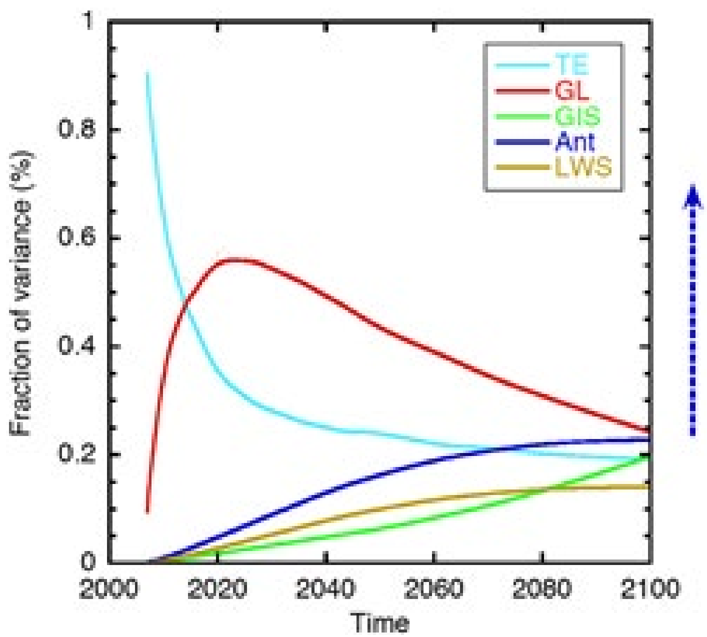

Figure 13 Evolution of the relative contribution to the total sea level variance of key factors: thermal expansion (TE), glaciers (GL), the Greenland ice sheet (GIS), Antarctica (Ant) and land water storage changes (LWS) as presented by Church et al. (2013). The dotted blue line indicates qualitatively the increase in the dynamic contribution of the Antarctic ice sheet if marine-based sectors of Antarctica collapse. Source: van de Wal et al. [16].

Appendix E: Average recurrence intervals for Vanuatu

For Vanuatu there is minimal difference between the 10/50/100-year ARI levels. Extreme sea levels tend to be driven more by tides/sea level and storm waves than wind-driven waves in the Pacific Islands because steep-sided islands get minimal wind setup (storm surge) compared to continental shelves [4]. This is evident in the 50-year ARI levels for the coastal points in Vanuatu, which are higher on exposed parts of the north and east sides of the central Vanuatu islands (Figure 14), consistent with the general passage of TCs from north to south (TC Harold was an exception), and the TC's clockwise rotation in the southern hemisphere.

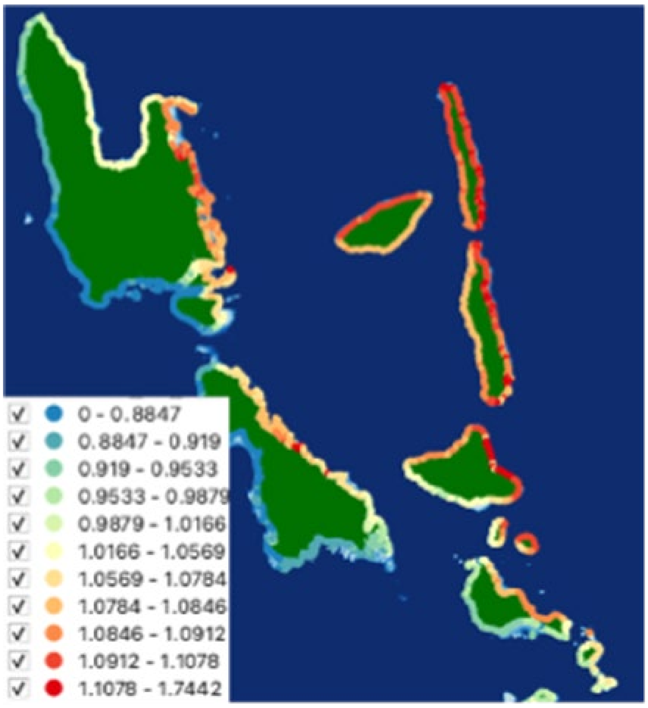

Figure 14 50-year ARI levels for the coastal points, which are higher (red) on exposed parts of the north and east sides of the central Vanuatu islands.

Another reason for the minimal differences between calculated ARIs is the relative rarity of TCs at any given coastal location, particularly places which are relatively sheltered from all but a near-direct hit. This causes the extreme value analysis (point-over threshold generalised Pareto distribution) to fit poorly to the data. An example is near the mouth of Luganville harbour – which is tucked in behind Maewo, Ambae, Pentacost, etc. (Figure 15). Statistical uncertainty remains for the most extreme events (50-year and 100-year ARIs) in many areas.

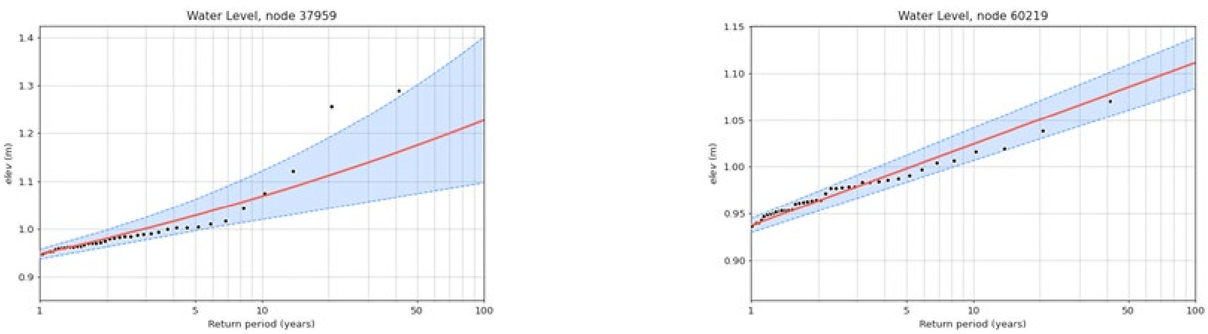

Figure 15 Extreme value analysis of storm surges for Luganville Harbour (left) and NE Pentecost (right). The black dots are 'actual' (simulated) events (the top two are TCs Harold and Pam) and the red line/blue cone is the EVA fit/95 % confidence intervals respectively.

Appendix F: Coastal points data sets

The CSV files below are currently stored on internal CSIRO cloud storage:

Hindcast_v3_coastal_points_schism_elev_POT_p99_8_GPD_ARI_baseline_20230718.csv

Hindcast_v3_coastal_points_schism_elev_POT_p99_8_GPD_ARI_rcp26_v20230718.csv

Hindcast_v3_coastal_points_schism_elev_POT_p99_8_GPD_ARI_rcp45_v20230718.csv

Hindcast_v3_coastal_points_schism_elev_POT_p99_8_GPD_ARI_rcp85_v20230718.csv

The ‘baseline’ file contains 10-year, 50-year and 100-year ARIs of extreme water levels for the current climate (1980–2020). It also contains other information, including longitudes/latitudes of the coastal points; the longitudes/latitudes and the ‘index’ of the nearest model’s ‘wet’ computational node; and EVA fit parameters:

The future projection files omit much of the ancillary information, since the points are in the same location as the baseline data and the EVA fitting remains (almost) the same. However, they link with the ‘node_idx/lat/long’ and include discrete 10/50/100 ARIs for each of the future 20-year periods centred on 2030, 2050, 2070 and 2090. These include sea level rise projections.

	longitude	latitude	node_idx	kns	node_lons	node_lats	depth	mean	max	p99	...	scale	10-year ARI	10-year lower ci	10-year upper ci	50-year ARI	50-year lower ci	50-year upper ci	100-year ARI	100-year lower ci	100-year upper ci
0	169.773	-20.247	97728	5	169.772	-20.246	1.110	0.029	1.288	0.642	...	0.039	0.967	0.899	1.044	1.160	1.008	1.348	1.263	1.057	1.531
1	169.771	-20.250	97735	10	169.772	-20.255	0.370	0.070	1.546	0.675	...	0.042	1.036	0.963	1.129	1.259	1.095	1.479	1.381	1.159	1.698
2	169.773	-20.247	97728	5	169.772	-20.246	1.110	0.029	1.288	0.642	...	0.039	0.967	0.902	1.061	1.160	1.018	1.404	1.263	1.073	1.613
3	169.794	-20.236	97922	10	169.796	-20.238	0.000	0.036	1.286	0.647	...	0.040	0.945	0.884	1.024	1.101	0.962	1.308	1.180	0.996	1.476
4	169.799	-20.238	97922	10	169.796	-20.238	0.000	0.036	1.286	0.647	...	0.040	0.945	0.888	1.028	1.101	0.980	1.302	1.180	1.022	1.461

To understand these fields, it helps to look at an example image of the model’s mesh/nodes for the coastal points and the coastline (Figure 7). Each point has an index number that can be found in the CSV files.

	node_idx	node_lons	node_lats	2030 10-year ARI	2030 10-year lower ci	2030 10-year upper ci	2030 50-year ARI	2030 50-year lower ci	2030 50-year upper ci	2030 100-year ARI	...	2070 100-year upper ci	2090 10-year ARI	2090 10-year lower ci	2090 10-year upper ci	2090 50-year ARI	2090 50-year lower ci	2090 50-year upper ci	2090 100-year ARI	2090 100-year lower ci	2090 100-year upper ci
0	97728	169.772	-20.246	1.106	1.004	1.224	1.298	1.113	1.528	1.402	...	2.166	1.710	1.465	2.043	1.903	1.574	2.347	2.006	1.623	2.530
1	97735	169.772	-20.255	1.175	1.068	1.309	1.398	1.200	1.660	1.520	...	2.333	1.780	1.529	2.128	2.003	1.661	2.479	2.124	1.725	2.697
2	97728	169.772	-20.246	1.106	1.007	1.242	1.298	1.123	1.584	1.402	...	2.248	1.710	1.468	2.061	1.903	1.584	2.403	2.006	1.639	2.612
3	97922	169.796	-20.238	1.084	0.989	1.204	1.240	1.067	1.488	1.319	...	2.111	1.688	1.450	2.023	1.844	1.528	2.308	1.924	1.562	2.475
4	97922	169.796	-20.238	1.084	0.993	1.209	1.240	1.085	1.483	1.319	...	2.096	1.688	1.454	2.028	1.844	1.546	2.302	1.924	1.588	2.461