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VANUATU

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CONTENTS

SEA-LEVEL RISE IMPACTS AND ADAPTATION IN VANUATU[1]

Sea-level will continue to increase during this century directly caused by global warming and melting of terrestrial ice. While Vanuatu cannot control global sea-level, it can manage how it affects the country by adapting. Staff analysis estimates the cost of sea-level rise under alternative adaptation strategies: (i) no-adaptation (ii) protection and (iii) planned retreat. Such analysis can help the government to identify trade-offs between efficiency and equity, and choose according to the preferences of the population, consistent with public finance objectives. Preliminary results show that complete protection of coastal areas in Vanuatu is costly while planned retreat from the coastline is the least-cost adaptation response. However, given the mountainous nature of the islands, only small areas of the main population centers of Port Vila and Luganville are at risk of being permanently inundated even with very high sea level rise.

A. Overview of Climate Trends and Projections

1. **Temperature is expected to continue increasing in Vanuatu until at least mid-century, but changes in precipitations and tropical cyclones are more uncertain.** Average temperature between 1985 and 2014 is estimated to be equal to 24.3 °C in Vanuatu, approximately 0.3 °C higher than in the period 1901-1930, which is a good proxy for its pre-industrial level. Recent warming has been modest and temperature changes have been mostly driven by year-to-year variability, but consensus estimates of warming from the most recent set of model simulations project that temperature will increase by between 0.9 and 1.2 °C in 2050, and between 0.8 and 2.1 °C in 2085, with respect to the 1985-2000 period. More warming than in consensus estimates cannot be excluded. In a high-emission, fast-warming scenario (90th percentile of the SSP3-7.0 emission scenario) temperature increases by 2.8 °C in 2070 in Vanuatu (Table 1). Higher temperatures can have far reaching impacts, including on labor productivity, agricultural yields, energy use, and sea-life. A positive finding is that, due to its geographic position, Vanuatu has experienced one of the lowest warming rates among countries and the warming trend is expected to be one of the slowest in the world.

2. **There are no significant trends and projected changes in total annual precipitations and tropical cyclones, but more extreme rainfall rates during tropical cyclones are likely**. Vanuatu is already one of the countries with the highest annual precipitation in the world. Small non-significant changes have been observed and small changes are projected, indicating that natural variability will continue to play a dominant role in future annual precipitations. The total number of tropical cyclones affecting Vanuatu declined during the period 1971-2020, but there is large uncertainty in detection and attribution to climate change of tropical cyclone trends in proximity of the country due to data limitations, poor quality of records, and strong natural

[1] Prepared by Emanuele Massetti (FAD).

Table 1. Vanuatu: Mean Surface Temperature: Historical Data and Projected Changes (°C)

	Level			
	1915	1975	2000	2020
Observed	24.0	23.9	24.3	24.3
	Change			
	Observed		Projected	
	1915 to 2000	2000 to 2030	2000 to 2050	2000 to 2085
SSP1-2.6		0.6 [0.4 to 0.8]	0.9 [0.5 , 1.2]	0.8 [0.5 , 1.4]
SSP2-4.5	0.3	0.6 [0.4 to 0.8]	1.0 [0.7 , 1.3]	1.5 [1.1 , 2.0]
SSP3-7.0		0.6 [0.5 to 0.8]	1.2 [0.9 , 1.5]	2.1 [1.5 , 2.8]

Source: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CRU data (Harris et al., 2020), and CMIP6 data (Copernicus Climate Change Service, Climate Data Store, 2021). Notes: All data in ºC. 1901-1930 (1915), 1961-1990 (1975), and 1985-2014 (2000) observed temperature from CRU. 2020 temperature is estimated using a linear regression of observed temperature from 2000 to 2021. Bias-adjusted ensemble median projections of temperature anomalies with respect to 1985-2014 (2000) data over 30-year time periods centered in 2030, 2050, and 2070 using CMIP6 data. In brackets, 10th and 90th percentiles of the model ensemble. The SSP1-2.6 scenario is in line with the Paris goal to keep global mean temperature increase below 2 ºC with respect to pre-industrial times. SSP2-4.5 represents continuation of present trends. SSP3-7.0 is a high emission scenario. The sum of warming from 1915 to 2000 and CMIP6 projections can be used to measure warming relative to pre-industrial level.

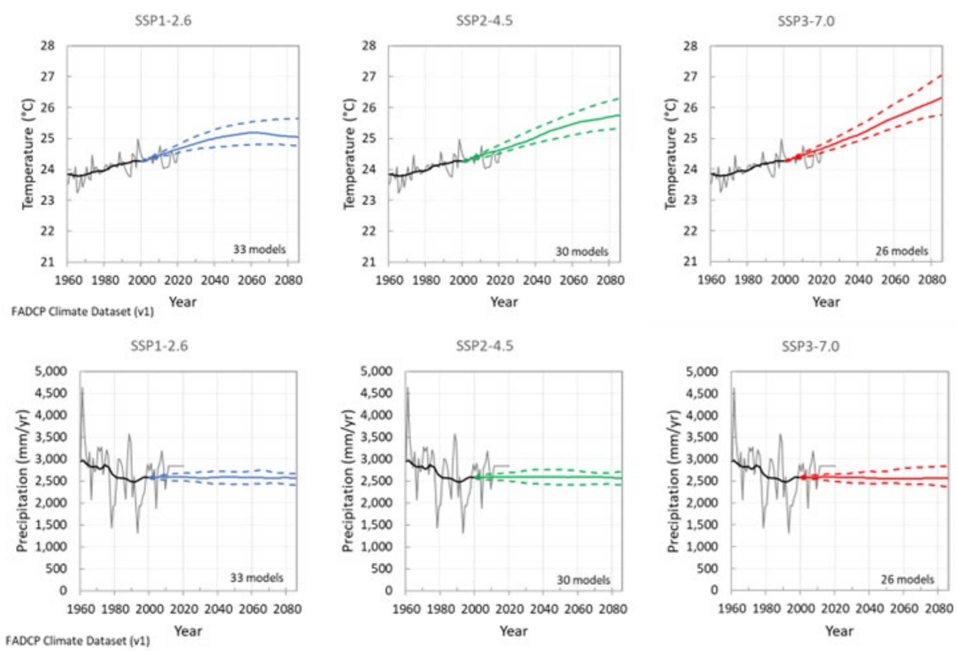
Table 2. Vanuatu: Summary Statistics of Temperature and Precipitation and Comparison with Other Countries

	Values	Ranking	Percentile	Median Country
Temperature, 2000 (°C)	24.3	100/215	53	23.4
Temperature change (2000 wrt 1915, observed, °C)	0.3	201/215	7	0.8
Temperature change (2050 wrt 2000, projected, SSP2-4.5, °C)	1.0	202/215	6	1.4
Precipitations, 2000 (mm/year)	2582	13/215	94	1097
Precipitation change (2050 wrt 2000, projected, SSP2-4.5, mm/year)	7.4	125/215	42	7.4
Precipitation change (2050 wrt 2000, projected, SSP2-4.5, %)	0.3%	131/215	39	1.6%

Source: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CMIP6 data (Copernicus Climate Change Service, Climate Data Store, 2021) and CRU data (Harris et al., 2020). Notes: CMIP6 bias-adjusted ensemble median projections of temperature and precipitation anomalies in a 30-year period centered around the chosen year with respect to CRU 1985-2014 (2000) averages. The observed temperature change with respect to 1901-1930 (1915) can be used as a proxy of warming relative to the pre-industrial period. The SSP2-4.5 scenario represents continuation of present trends.

variability (CSIRO, Federation University, Climate Comms, 2023, p.4; CSIRO and SPREP, 2022; McGree et al., 2022). The share of total annual precipitations falling during tropical cyclones has increased during 1994-2018 compared with 1970-1993, which is in line with observations in other parts of the world and a probable long-term trend (CSIRO, Federation University, Climate Comms, 2023a, p.5). Projecting frequency and intensity of future tropical cyclones (TC) is subject to large uncertainties. There is a moderate level of confidence in predicting a decrease in the average number of TC globally, with an increase in the proportion of severe cyclones. Analysis by the Australian climate research center for Vanuatu projects an overall decline in the frequency of TC affecting Vanuatu across all intensities (CSIRO, Federation University, Climate Comms, 2023, pp. 7-8)[2]. TC intensity is measured using maximum sustained wind speed, but TC damages are also a function of rainfall intensity, which is expected to increase due to higher atmospheric moisture content (IPCC, 2021). Models reviewed by CSIRO for the south-west Pacific indicate a median 8 percent increase in TC rainfall for a +2°C global warming scenario (CSIRO, Federation University, Climate Comms, 2023, p. 10). The net economic impact of all these changes on expected future damages from tropical cyclones is uncertain and is beyond the scope of this assessment.

Figure 1. Summary Statistics of Temperature and Precipitation and Comparison with Other Countries



Source: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CRU data (Harris et al., 2020), and CMIP6 data (Copernicus Climate Change Service, Climate Data Store, 2021: CMIP6 climate projections).

Notes: The gray line describes historical mean annual precipitation/temperature based on observations (CRU). The black line describes the 30-year moving average of historical data centered around each 30-year period. Colored lines represent the median and the 80 percent range of temperature anomalies (10th and 90th percentiles) added to the CRU value (thick black line in the year 2000). SSP1-2.6 scenario is in line with the Paris goal to keep global mean temperature increase below 2°C with respect to pre-industrial times. SSP2-4.5 represents continuation of present trends. SSP3-7.0 is a high emission scenario.

3. **Marine heat waves (MHW) are projected to increase in frequency and intensity, following global warming trends, with risks for marine life that add to ongoing ocean acidification**. The frequency of MHW is increasing across the whole country even assuming a low emission scenario, with a faster trend in the northern regions of the archipelago (CSIRO, SPREP and VMGD, 2023). This trend is discernible amid large natural variability driven by the El Niño-Southern

[2] Stronger TC become more likely than weaker TC, but the overall decline in the total number of TC is such that stronger TC become less frequent than in the present.

Oscillation (ENSO). Warmer waters have largely negative impacts on marine life, including corals which are also threatened by the acidification of the oceans driven by increasing carbon dioxide concentrations. Additionally, deoxygenation of ocean waters, exacerbated by marine rising temperatures, poses a further threat to the ecosystems, reducing the availability of oxygen necessary for marine species to survive.

4. Sea-level is increasing and will continue to increase throughout at least this century, even assuming a low emission scenario. The primary sources of global mean sea-level increase are thermal expansion directly caused by global warming and melting of land-based ice mass, most of which is in Greenland and Antarctica (Kopp et al., 2014). A slow but persistent response of ice masses to higher temperature will cause sea-level to increase for decades and possibly centuries after global mean temperature stabilizes. As a result, there is no doubt that sea-level will continue to increase during this century, but uncertainty remains on its extent. Thermal expansion and melting of the Greenland Ice sheet are projected to be the main sources of sea-level rise in this century, with relatively narrow uncertainty ranges. The contribution to sea-level rise of Antarctic Ice Sheet melting is instead very uncertain, going from slightly negative (due to increased snow accumulation) to very large (Kopp et al., 2014). Projections of global mean-sea level rise are useful to monitor global trends but are not accurate to predict local impacts and support adaptation decisions (Kopp et al., 2014; Diaz, 2016). Local sea-level rise can differ from global mean sea-level rise due to multiple factors, including local vertical land movement (for example, due to tectonics) (Kopp et al., 2014). For these reasons, the analysis of the cost of sea-level rise in this Annex relies on probabilistic local sea-level rise projections, which account for regional sea-level rise, local vertical land movements, and uncertainty in the range of sea-level rise (Kopp et al., 2014; Diaz, 2016). More recent projections of SLR (Fox-Kemper et al., 2021) are substantially in line with those in Kopp et al. (2014), with the exception of a new low-confidence extreme emissions and extreme fast Antarctica Ice Sheet melting projection.[3]

5. Median projections for Vanuatu using a moderate emission scenario indicate that by the end of the century sea-level may increase by 0.64 m with respect to its level in 2000 (Table 3 and Figure 2). With an emission scenario in line with the Paris goal of keeping global mean temperature increase below 2 °C, sea-level is projected to increase by 0.54 m (Table 3). With a very high emission scenario, sea-level is projected to increase by 0.82 m (Table 3). The inclusion of regional and local factors affecting local sea-level rise led to a slightly higher levels than global mean-sea level rise (Table 3 and Figure 2). The analysis of sea-level rise costs and adaptation presented in the next section uses the moderate emission scenario because it is roughly in line with

[3] In the most recent set of IPCC projections (Fox-Kemper et al., 2021) the SSP2-4.5 scenario is comparable to the RCP4.5 scenario in Kopp et al. (2014) and finds 0.56 m of SLR in 2100 in Vanuatu, instead of 0.54 m. The SSP5-8.5 scenario is comparable to the RCP 8.5 scenario and projects exactly 0.82m of SLR in 2100 as in Kopp et al. (2014). The 95th percentiles of the SSP2-4.5 and SSP5-8.5 scenarios are approximately 0.1 m higher than in Kopp et al. (2014). The new projections also consider a low confidence (limited empirical evidence), very fast SLR in the unlikely extremely high emission scenario that predicts much higher SLR at the extreme of its distribution. Data extracted for Port Vila, from Garner et al. (2021).

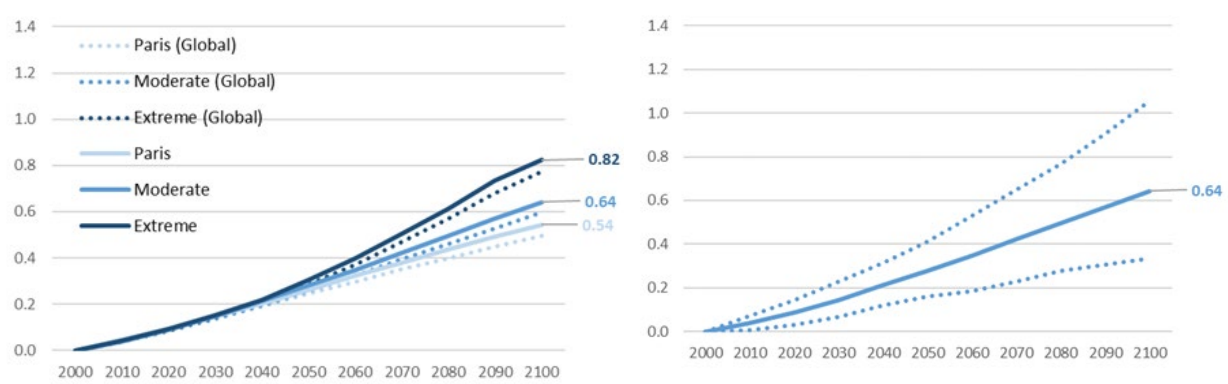
a scenario in which emissions grow along present trends and it considers the range of sea-level rise uncertainty for this level of emissions.

Table 3. Vanuatu: Sea-Level Rise Projections Relative to 2000 Level (Meters)

	2030	2050	2070	2100
Global Mean				
Paris (RCP2.6)	0.14 [0.10 , 0.18]	0.25 [0.18 , 0.33]	0.35 [0.23 , 0.51]	0.50 [0.30 , 0.82]
Moderate (RCP4.5)	0.14 [0.10 , 0.18]	0.26 [0.18 , 0.35]	0.39 [0.26 , 0.56]	0.60 [0.35 , 0.94]
Extreme (RCP8.5)	0.14 [0.11 , 0.18]	0.29 [0.21 , 0.38]	0.47 [0.33 , 0.66]	0.77 [0.51 , 1.19]
Vanuatu				
Baseline	0.00 [-0.04 , 0.03]	0.00 [-0.06 , 0.05]	0.00 [-0.08 , 0.07]	-0.01 [-0.12 , 0.11]
Paris (RCP2.6)	0.15 [0.08 , 0.22]	0.26 [0.16 , 0.38]	0.38 [0.22 , 0.58]	0.54 [0.29 , 0.93]
Moderate (RCP4.5)	0.15 [0.07 , 0.23]	0.28 [0.16 , 0.41]	0.42 [0.23 , 0.65]	0.64 [0.34 , 1.05]
Extreme (RCP8.5)	0.15 [0.08 , 0.22]	0.30 [0.18 , 0.44]	0.50 [0.30 , 0.76]	0.82 [0.48 , 1.33]

Source: Sea-level rise projections from Kopp et al. (2014) derived from the CIAM model database (Diaz, 2016).
Notes: Global and Local Sea-Level Rise (SLR) probabilistic projections until 2100 under three emission scenarios (Paris - RCP 2.6; Moderate - RCP 4.5; Extreme - RCP 8.5). The range in brackets represents the 5th and 95th percentiles of the distribution of SLR for each emission scenario. Local SLR projections include information on local climate change induced SLR rates and baseline projections of local vertical land movement (subsidence or uplifting) not caused by climate change.

Figure 2. Sea-Level Rise Projections Relative to 2000 Level (Meters)



Source: Sea-level rise projections from Kopp et al. (2014) derived from the CIAM model database (Diaz, 2016).
Notes: Left: Local (solid) and Global (dotted) Sea-Level Rise (SLR) probabilistic projections until 2100 under three emission scenarios (Paris - RCP 2.6; Moderate - RCP 4.5; Extreme - RCP 8.5). Median SLR for each emission scenario. Right: local SLR probabilistic projections using the Moderate (RCP 4.5) emission scenario. Solid lines depict median SLR, dotted lines depict the 5th and 95th percentiles of the distribution to account for uncertainty in the speed of sea-level rise and tipping points in Greenland and Antarctica Ice Sheets melting.

B. Sea-Level Rise Impacts and Adaptation

6. Vanuatu cannot control global sea-level, but it can manage how it affects the country by adapting. Mitigation policy is key to limiting the speed of sea-level rise (SLR) during this century and the overall extent of SLR in future centuries, but adaptation plays a crucial role to limit the unavoidable impacts of SLR.

7. Using a state-of-the-art model of SLR costs and adaptation, IMF staff estimates the net present value of three main adaptation scenarios (Box 1). (i) No Adaptation – society reacts to SLR by relocating reactively, after land is inundated. No protection is built, and capital losses are large. (ii) Protection – society chooses the protection plan against SLR with the largest net-present value by anticipating its effects without relocating people or assets. (iii) Retreat – society plans retreat from the coastline by anticipating SLR, letting capital depreciate and eventually abandoning, and moving population before it is at risk. Variations of the Protection scenario assume construction of defenses to avoid storm flooding for 1/10, 1/100, 1/1,000 and 1/10,000 years storm surge events. Variations of the Retreat scenario assume a retreat perimeter to deal with permanent sea-level inundation alone (Retreat 1), or also including 1/10 to 1/10,000 years storm surge events. Finally, the Least-Cost scenario is calculated by comparing costs across all scenarios for each coastal segment independently.

Figure 3. Map of Vanuatu with CIAM Coastal Segments

Source: IMF Staff based on coastal segment characteristics from the CIAM model (Diaz, 2016), country boundaries from EuroGeographics and UN-FAO, and free Natural Hearth vector and raster map data @ naturalearthdata.com.
Notes: Country's coastline is divided in 16 segments. Each dot in the map indicates the center of a coastal segment. Coastal segments vary in length from 48.4 Km to 372.7 Km, with a median length equal to 110.8 Km.

8. IMF Staff estimates using CIAM find that the cost of SLR can be equal to 0.8 percent of GDP annually without adaptation, using a moderate emission scenario (Figure 5). Risks associated with lower or higher SLR are balanced, with 80 percent of projections using the moderate RCP 45 scenario falling in the 0.5 to 1.0 percent range. With an emission scenario in line with the

Paris 2 °C goal (RCP 2.6), the cost of SLR is estimated to be equal to 0.7 percent of GDP annually, ranging from 0.4 to 0.9 percent. With an extreme emission scenario (RCP 8.5), costs increase to 0.9 percent of GDP on average annually, ranging from 0.7 to 1.2 percent. About 2/3 of the cost is caused by permanent loss of land and not fully depreciated assets (Inundation), and by the disutility of relocating population without sufficient long-term planning (Relocation). The remaining 1/3 is caused by impacts of storm surges on the population and on capital. These costs measure welfare losses and are the appropriate metric to estimate the full economic impact of SLR. However, they cannot be translated into GDP losses or other fiscal impacts without other models or additional assumptions. The literature uses general equilibrium models to translate loss of capital and land into long-term macroeconomic impacts, including global trade effects (e.g., Bosello et al., 2012). Alternatively, it is possible to derive first-order approximations of the fiscal costs of SLR by assuming how much of the social cost of SLR is either suffered by the public sector or compensated with public finances. Direct losses may derive from reconstruction costs of public assets and purchase of new land for public use. Losses of private capital and private land may have an impact on public finances if they affect tax revenues, or if the government compensates for private losses. Increased spending on social programs aimed at easing disutility costs of relocation from inundated areas can lead to higher expenses. If the government assumes full responsibility for all losses, including the adverse effects of relocation, the costs presented in can be interpreted as an upper bound to government financing needs.

Figure 4. High-Resolution Visualization of SLR in Representative Coastal Areas

(a)

(b)

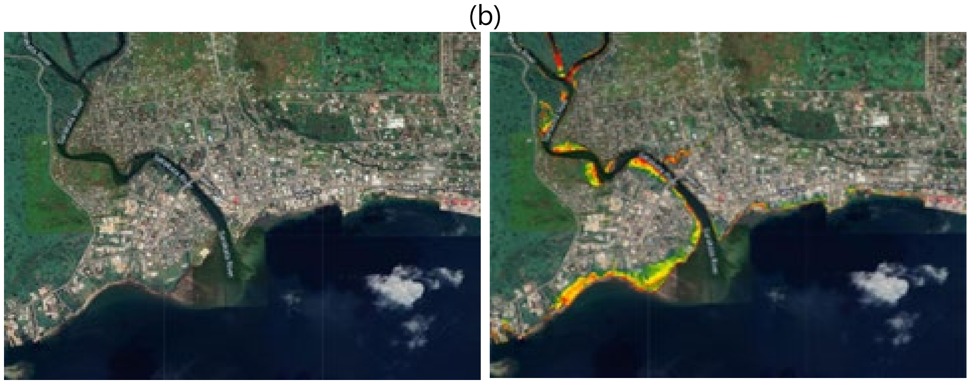
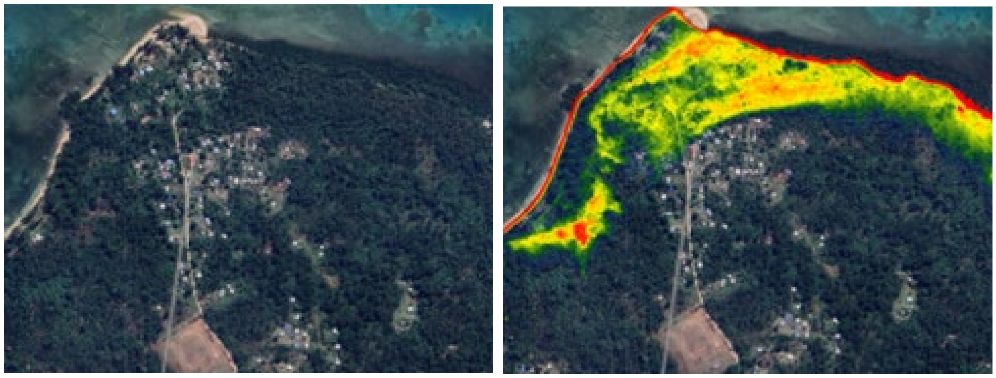


Figure 4. High-Resolution Visualization of SLR in Representative Coastal Areas (Concluded)

(c)

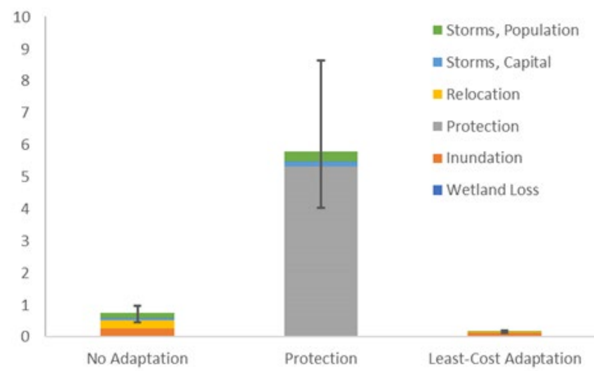


Source: Vanuatu Climate Futures Portal (consulted on April 19, 2024).
Notes: Notes: (a) Port Vila, 17°44'33"S 168°18'58"E; (b) Luganville 15°30'45"S 167°10'20"E; (c) Paonangisu, 17°31'42"S 168°24'07"E. Right column shows SCHISM-WWMIII inundation projections for extreme sea levels with an average recurrence of 100 years for the Vanuatu coast in 2080-2099 which accounts for sea-level variations due to tides, waves, storm surge and background variability, combined with projected sea-level rise from the Next Generation Climate Projections for the Western Tropical Pacific with the extreme RCP 8.5 emission scenario. Red colors indicate areas with higher depth. Mapped using Google Earth Engine.

9. **Complete protection of coastal areas is very expensive and not a cost-effective adaptation (Figure 5), a result in line with other studies in literature**. CIAM calculates the cost of SLR and the cost of protection considering many factors, including coastal topography, distribution of population and capital, and protection costs. The coastline of the country is divided into 16 segments that have similar characteristics – high resolution for a global model (Figure 3), but possibly too coarse to estimate costs with precision. To complement CIAM's analysis with higher resolution data, maps of sea-level rise obtained from the Vanuatu Climate Futures Portal have been used to visualize the impact of SLR on infrastructure and the population using Google Earth Engine (Figure 4). This high-resolution analysis reveals that, even with very high SLR, only small areas of main population centers are permanently inundated (panels (a) and (b)). Protection of these areas to avoid inundation and relocation costs is possible, but it is estimated to be very costly in Vanuatu. Contrary to what is found in most countries, protection of the coastline is more costly than doing nothing in CIAM's estimates (Figure 5). Using a different method and data, Hinkel et al. (2018, SM p. 8) reach the same conclusion: protection is never cost-effective in any part of Vanuatu using a large set of robustness tests. The discounted total cost of SLR without protection in Hinkel et al. (2018) is estimated to be equal to 0.5 percent of discounted total GDP, a result similar to what obtained using CIAM. As a comparison, strengthening public and other major infrastructure and development projects against current and projected risks to minimize losses is estimated to cost approximately one percent of GDP annually between 2021 and 2030 in Vanuatu's Revised and Enhanced 1st Nationally Determined Contribution.[4]

[4] $165M between 2021 and 2030. Source: https://unfccc.int/sites/default/files/NDC/2022-08/Vanuatu%20NDC%20Revised%20and%20Enhanced.pdf

Figure 5. Annual Average Cost of Sea-Level Rise, 2020-2099 (In percent of GDP)



Source: IMF Staff using the CIAM model (Diaz, 2016).
Notes: Average annual cost. Whiskers on top of each bar indicate the range of total cost using the 5th and 95th percentile of the probabilistic distribution of sea-level rise. Due to the highly non-linear nature of coastal impacts, adaptation costs, and effectiveness of adaptation measures, ranges are not always symmetric around total costs.

10. **The least-cost adaptation response in Vanuatu is planned retreat from the coastline, which can cut costs to 0.16 percent of GDP annually (0.11 to 0.21 range) (Figure 5).**[5] This implies that capital in areas that are predicted to be inundated is left to depreciate and rebuilt in other areas. Population retreat from this area is planned, avoiding large relocation costs from sudden movements following inundation. Panel (c) of (Figure 4) helps visualize the trade-offs between protection and planned retreat in the case of a coastal community. SLR is projected to inundate a large fraction of the coastal village Paonangisu. Protecting this village is possible, but it can be very expensive. Planned retreat implies that the population slowly abandons assets in areas that will be inundated and rebuilds them slightly more inland, without need for long-distance migration. In some areas of Vanuatu, this may require retreat to areas where villages were originally located, before they slowly migrated closer to the coastline (Ballu et al., 2011). The main cost of planned retreat is permanent loss of land, which is estimated using the value of land where the population moves. For example, in the case of Paonangisu, some of the agricultural or marginal land at the outskirts of the village will be converted to residential areas by the relocated population. The opportunity cost of this land is the correct measure of the cost of inundation. CIAM uses the value of agricultural land in the country as a proxy of opportunity cost of land lost due to SLR. Relocation disutility costs and coastal inundated land account for virtually all planned retreat costs. The fiscal cost of compensations is thus equal to approximately 0.16 percent of GDP annually. As the cost of protection is very large, even under the assumption of much higher disutility costs from relocation and higher land values for inundated land the result that planned retreat is cheaper than complete protection is expected to hold. Very localized interventions to protect specific assets at risk may be cost-effective but they can only be identified using extremely high-resolution coastal engineering studies that are beyond the scope of this preliminary analysis.

[5] The cost of SLR projected using the RCP 8.5 emission scenario is equal to 0.2 percent of GDP annually using the median projection, and it ranges from 0.14 to 0.25 percent using the 5th and 95th percentiles of the distribution of SLR for the same emission scenario.

11. Planned retreat is the least-cost adaptation option according to CIAM and other studies, but it is not necessarily the preferred option for society. The lower cost of planned retreat compared to protection implies that compensation of retreat losses is less expensive than protection. The government should be aware of the trade-offs between efficiency and equity, and choose accordingly to the preferences of the population, consistently with public finance objectives.

12. This analysis is preliminary because more granular data is necessary to exactly determine the optimal adaptation mix, but it shows that cost-benefit analysis (CBA) can play a significant role in helping authorities select their preferred adaptation strategy. Maps like those shown in Figure 4 can be used to more precisely estimate the cost of different adaptation strategies. CBA can be challenging, but even preliminary and incomplete assessments are useful to identify trade-offs and the most attractive policy options using a transparent and systematic approach (Bellon and Massetti, 2022). Best practices can be drawn from coastal protection analysis and policies in other countries, for instance in the Netherlands, where there is a long-standing tradition of using CBA and cost-effectiveness analysis for flood risk management and water governance. This tradition started in 1954 with the pioneering CBA of the Delta Works by Tinbergen (1954) and continues to this day (Bos and Zwaneveld, 2017).

Box 1. Estimating the Cost of Sea-Level Rise and Adaptation

The analysis of sea-level rise impacts, and adaptation options is done using complex models that rely on necessary simplifications but provide important insights. While there is uncertainty on the exact extent and cost of damages from SLR and on the cost of protection measures, there is consensus in this literature that long-term planning of adaptation can be highly effective at containing physical impacts and costs of SLR. For example, the large EU-funded research project PESETA IV finds that coastal protection can reduce SLR damages in the EU by approximately 90 percent (Vousdoukas et al. 2020, Table 6). Model simulations fully agree that adaptation can be highly effective but may differ on the optimal mix of adaptation measures – e.g., hard protection, nature-based solutions, planned retreat – because they use different data, use different climate scenarios, or work under different normative criteria. There is also consensus that the transformations needed to adapt to SLR, while technologically feasible and economically sound, are complex and require strong governance (Hinkel et al., 2018).

IMF staff uses the state-of-the-art Coastal Impact and Adaptation Model (CIAM) to estimate the cost of sea-level rise under alternative adaptation strategies. CIAM is a global model used to estimate the economic cost and benefits of adaptation to sea-level rise (Diaz, 2016). The global coastline is divided into more than 12,000 segments of different length grouped by country. Vanuatu's coastline is modeled using 16 segments (Figure 3), varying in length from 48.4 Km to 372.7 Km, with a median length equal to 110.8 Km. Each segment is further divided into areas of different elevation. For each segment, the model has data on capital, population, and wetland coverage at different elevations. By using projections of local sea-level rise from Kopp et al. (2014), it is possible to estimate the areas that will be inundated and the amount of capital and population at risk. Storms cause periodic inundations on top of sea-level rise. The model does not consider increased risks from river floods.

The model calculates the cost of SLR—protection costs plus residual losses—under alternative adaptation options:

The ***no-adaptation*** scenario assumes that population does not move until the sea inundates the area where they live and then relocates to areas with higher elevation. Society keeps building and maintaining capital

Box 1. Estimating the Cost of Sea-Level Rise and Adaptation (Concluded)

until inundation causes irreversible losses and capital is abandoned. The cost of sea-level rise is calculated as the sum of the residual value of capital that is abandoned, demolition costs, and the value of land that is inundated. The model uses the rental value of agricultural land in proximity to the coastline, following Yohe et al. (1990), because as SLR progresses, coastal proximity rents will shift from land that is inundated to adjacent land. Population density and development opportunity costs are assumed to be capitalized in agricultural land values. The disutility cost of reactive migration is monetized.

- At the opposite, a ***protection*** scenario assumes that society invests in cost-effective seawalls and other barriers along the entire coastline to avoid inundation from sea-level rise, but storms can still periodically inundate protected areas if protection is not sufficiently high. Capital and land are not lost, the population does not move, but storms periodically cause capital and human losses. The cost of SLR is equal to the cost of protection plus the expected value of the cost of storms.
- Another adaptation option relies on ***planned retreat*** from areas that will be subject to inundation. The goal of retreat is to keep using coastal areas without building new capital and by letting the existing capital depreciate. For example, a coastal road is used until it needs major retrofitting investment. Then, a new coastal road is built in-land on higher grounds. This strategy accepts that land and some residual value of capital will be lost, but it avoids coastal protection costs. The population gradually moves to higher grounds before areas are inundated. This usually does not require migration to distant places, but rather relocation within the same coastal area. The cost of SLR is equal to the sum of the residual cost of capital, the value of inundated land, and the disutility cost of relocation.
- The model considers variants of protection and retreat scenarios to deal with risks from storm surge floods. For example, the model calculates the height of the coastal protections to contain SLR and increasingly large storm surges (1/10, 1/100, 1/1,000 and 1/10,000 year events). In the base scenario (Retreat 1), the retreat perimeter is calculated to only deal with permanent inundation of land, but the retreat perimeter can be pushed to also avoid storm surges (from 1/10 to 1/10,000 year events).
- For each coastal segment, the model calculates the net present value of SLR costs for each adaptation strategy. Loss of life is monetized using the Value of Statistical Life and loss of wetland due to either SLR or protection of barriers that impede the normal circulation of tidal waters is monetized using estimates of willingness to pay for biodiversity preservation.
- The cost of building and maintaining seawalls, and other key parameters are from literature. Storm surge costs are incremental with respect to a baseline scenario in which storms occur without SLR.
- By comparing SLR costs across all scenarios it is possible to find the ***least-cost adaptation strategy*** for each coastal segment and to calculate the lowest possible cost of SLR for the country. Coastal protection is usually the least-cost strategy in areas with large existing capital and high population density. Planned retreat is usually the least-cost strategy in areas with low capital and population density. The optimal height of coastal protection infrastructure and the optimal retreat perimeter vary on many factors, including projected incremental costs of protection, the opportunity cost of not using land that would normally not be flooded, capital and population at risk, sea-level rise scenarios.

Despite many uncertainties and some necessary simplifying assumptions, CIAM provides a useful framework to systematically study costs and benefits of alternative adaptation strategies to SLR. More granular coastal modeling and more accurate mapping of assets can provide a more precise assessment of costs and benefits, but the key insights developed with a baseline version provide a useful starting point to deal with a complex, multidecadal challenge

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