Tropical cyclone observations, trends and projections for Vanuatu

EXPLAINER

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CSIRO

SPREP
Secretariat of the Pacific Regional Environment Programme

GREEN CLIMATE FUND

This publication should be cited as:

CSIRO, Federation University, Climate Comms (2023). Tropical cyclone 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 Tony Rafter and Kathy McInnes (CSIRO) for providing helpful comments.

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

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Summary

Observations and trends

Vanuatu had an average of 31 tropical cyclones (TCs) per decade within a 500 km buffer surrounding the country over the period of available data (1971–2021) [1]. About 15 % of annual rainfall in Vanuatu is associated with TCs. More TCs occurred during La Niña events (~13 per decade) compared with El Niño and neutral events (~9 per decade) during 1971–2021 [1].

Historical TC trends indicate:

- The average number of TCs passing within 500 km of Vanuatu has declined from ~36 TCs per decade to ~26 TCs per decade between the two periods 1971–1995 and 1996–2021; a ~28 % decline [1, 2].
- The intensity of TCs (defined as mean TC wind speed) passing within 500 km of Vanuatu has increased by ~15 % between 1971–1995 and 1996–2021 [1, 2].
- The proportion of severe TCs (category 3-5) passing within 500 km has increased from 45 % to 57 % between the period 1971–1995 and 1996–2021 [1, 2].
- The maximum daily rainfall associated with TCs has increased by ~20 mm per day between the periods 1970–1993 and 1994–2018 [3].

Projections

- Under a high greenhouse gas emissions scenario (RCP8.5), the average number of cyclones passing within 500 km of Vanuatu is projected to decrease by ~12 % by the end of the 21st century (low-medium confidence) [4]
- Average cyclone wind speed intensity is projected to increase slightly by the end of the century, and severe cyclone wind speed intensity (100-year return period) is projected to increase 2–6 % (medium confidence) [1, 4].
- Sea level rise and an increase in extreme sea level events are projected, which may exacerbate cyclone impacts near the coast (medium-high confidence) [1, 4-7].
- TC-related rainfall rates are projected to increase (high confidence) [3, 4].
- While overall TC frequency is projected to decrease, more cyclones are projected in future during El Niño conditions compared with present-climate El Niño conditions, with fewer cyclones in future during La Niña conditions compared with present-climate La Niña conditions (low-medium confidence) [8].
- There may be more extreme El Niños and more extreme La Niñas [9, 10] (medium confidence).
- Poleward movement of TCs is possible, but there is substantial uncertainty (low-medium confidence) [4, 11-14].

Caveats

There are several factors that make the interpretation of both observed and projected TC changes difficult. Amongst these factors are the following:

- Presence of large natural variability and lack of consistent long-term observations often complicate trend analysis of TC characteristics.
- Differences in climate model projections of TC-related environmental variables, from different climate models and different analysis methods, can lead to large variations in projected changes of TC attributes, such as frequency and intensity.
- Some climate models poorly simulate observed TC attributes, so an assessment of climate model performance should guide the selection of the best models for TC projections.
- Uncertainties in climate models projections of ENSO have implications for TC frequency and intensity projections, and associated confidence ratings.

Tropical cyclone definition

Tropical cyclones are rapidly rotating storms that originate over tropical oceans that are typically above 25.5 °C [15], and at least 5° of latitude away from the equator where there is sufficient Coriolis force to create rotation (clockwise in the southern hemisphere, anti-clockwise in the northern hemisphere). In the Australian and the South Pacific Ocean basins, a weather system is classified as a TC when it has a 10-minute sustained mean wind speed of at least 17.5 metres per second (m/s). In these basins, TCs are classified into five categories (Table 1): Category 1 (weakest) to Category 5 (strongest). Systems that reach Category 3 and above are often referred to as severe TCs.

Table 1 The Australian/Fiji TC intensity scale is used to classify TCs from categories 1 to 5 [16]. Maximum mean wind refers to 10-minute sustained wind speed. Note that the TC wind speed used for analyses are in m/s.

Category	Typical effects	Maximum Mean Wind		
		km/hr	m/s	kts
1	Damaging winds. Negligible house damage. Damage to some crops and trees. Craft may drag moorings.	63–88	17.5–24.4	34.0–47.5
2	Destructive winds. Minor house damage. Significant damage to signs and trees. Heavy damage to some crops. Risk of power failure. Small crafts may break moorings.	89–117	24.5–32.5	47.6–63.2
3	Very destructive winds. Some roof and structural damage. Some caravans destroyed. Power failures are likely (e.g. TCs Lusi, 2014; Keni, 2018)	118–159	32.6–44.2	63.3–85.9
4	Significant roofing loss and structural damage. Many caravans destroyed and blown away. Dangerous airborne debris. Widespread power failures. (e.g. TCs Uma, 1987; Betsy, 1992; Prema, 1993; Ivy, 2004; Judy, 2023)	160–200	44.3–55.6	86.0–108.0
5	Extremely dangerous with widespread destruction (e.g. TCs Pam, 2015; Harold, 2020; Kevin, 2023)	Greater than 200	Greater than 55.6	Greater than 108.0

Background

Tropical cyclones usually affect Vanuatu during the southern hemisphere 'cyclone season', which is from November to April, but can also occasionally occur outside this period [17]. Cyclones are one of the costliest natural hazards impacting communities in Pacific Island Countries due to their high exposure and vulnerability, which limits adaptive capacity [7]. Vanuatu, which is the most vulnerable nation in the world to the risk of natural hazards [18-21], lies in a region where TC frequency is relatively high (Figure 1). Vanuatu's Exclusive Economic Zone (within 370 km of the country) had 2.4 TCs per year, on average, during 1971–2019 [22], or 3.1 TCs per year within 500 km during 1971-2021 [1].

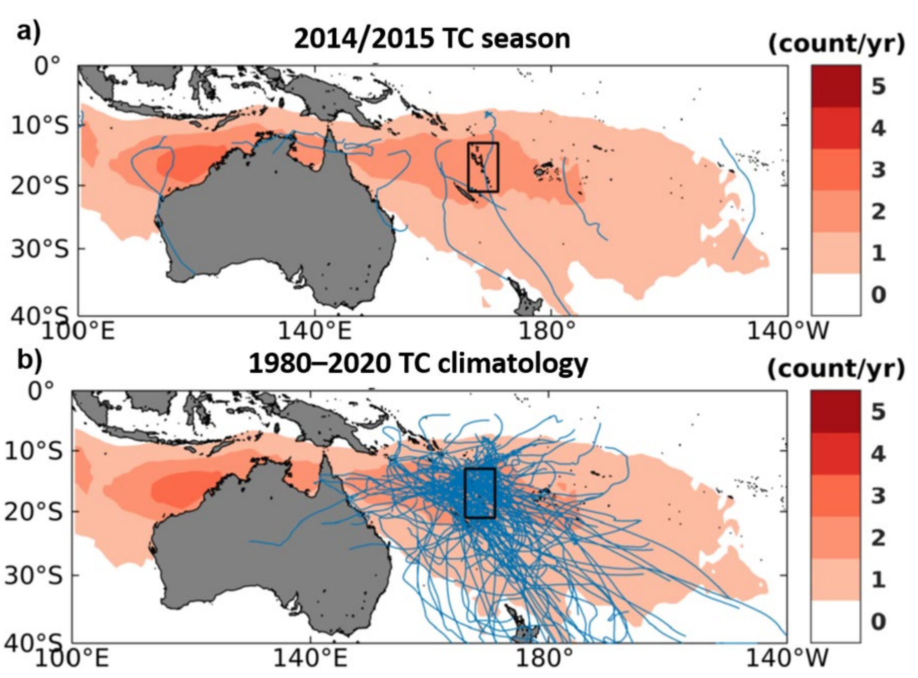


Figure 1 Tropical cyclone (TC) occurrence (shading) and tracks (lines), with Vanuatu contained in the box. (a) 2014/2015 TC season showing the track of the severe TC Pam which struck Vanuatu during March 2015. (b) Tracks of all TCs passing near Vanuatu during 1980–2020. The TC count per year is the annual average occurrence of a track within a 5° x 5° latitude–longitude box. TC data are from the International Best Track Archive for Climate Stewardship (IBTrACS; [23]) and assessed following the methodology in Widlansky et al. (2019) [24].

The strong winds, heavy rainfall, and storm surges associated with TCs often have devastating consequences for built infrastructure, services, businesses, livelihoods, health, the natural environment, and the national economy [6, 21, 25, 26]. For example, severe TC Pam in 2015 (Figure 1a and Figure 2a) caused a total economic loss of VT 48.6 billion in Vanuatu – equivalent to 64 % of Vanuatu's gross domestic product [21]. In April 2020, TC Harold caused a total economic loss of VT 24 billion [43]. In March 2023, Vanuatu witnessed unprecedented back-to-back TCs (severe TC Kevin and TC Judy) that caused widespread destruction across the provinces (Figure 2b,c) [27-30], affecting at least 80 % of the country's population [27] with 26 % of the arterial road network also being inaccessible and hampering disaster response [27].

The Vanuatu Meteorology and Geo-hazards Department (VMGD) provides more information about cyclone risk, forecasts, tracks and warnings: https://www.vmgd.gov.vu/vmgd/index.php/forecast-division/tropical-cyclone

a)

b)

c)

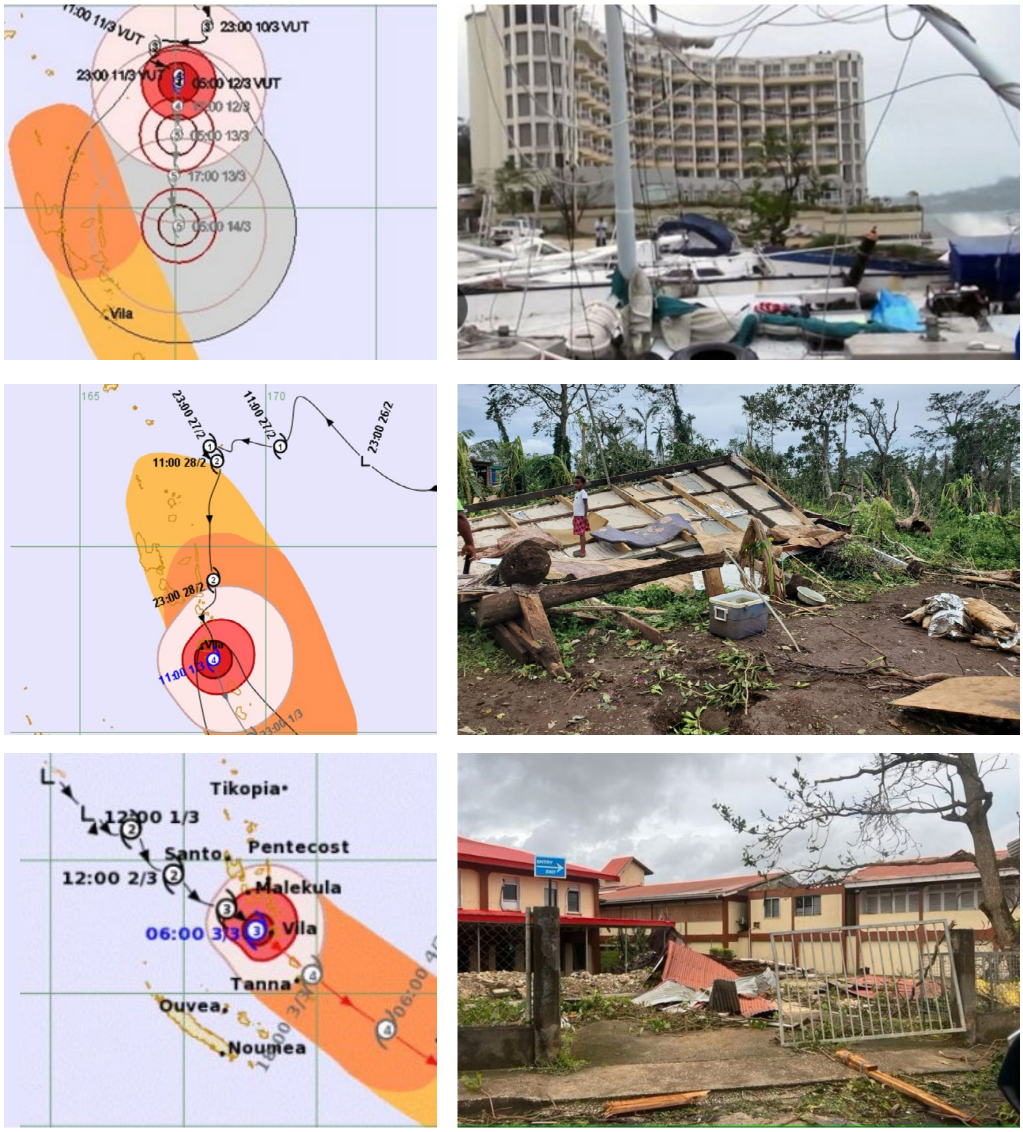


Figure 2 TC threat maps (left column) and examples of impacts (right column) of some notable cyclones that affected Vanuatu in recent years, including (a) TC Pam (2015), (b) TC Judy (2023) and (c) TC Kevin (2023).

Observed tropical cyclones and impacts

Substantial limitations in the availability and quality of observed TC records for Vanuatu and the broader PICs, compounded by strong natural variability, have created barriers to the detection and attribution of TC trends [6, 17]. TC track data from the South Pacific Enhanced Archive of Tropical Cyclones (SPEArTC; [31]) is considered the most comprehensive collection of quality-controlled data for the South Pacific region [23]. Various studies have used the SPEArTC data to report trends in TCs for the wider South Pacific region [32-35] .

The southern hemisphere TC season is defined from July of the current year to June of the following year, with the latter representing a particular TC season, e.g. July 2020 to June 2021 is labelled as the 2021 TC season. Analysis of the 1971 to 2021 TC seasons for Vanuatu using the SPEArTC database has recently been undertaken [1] for three buffers of 500 km, 250 km, and 50 km around Vanuatu (Figure 3a) to determine the current frequency and intensity of TCs. On average, ~31, 22 and 11 TCs per decade crossed the 500 km, 250 km, and 50 km buffer regions, respectively.

The annual number of TCs affecting Vanuatu declined during 1971–2021 (Figure 3b). The average number of TCs passing within 500 km of Vanuatu declined from ~36 TCs per decade to ~26 TCs per decade between the two periods 1971–1995 and 1996–2021, i.e. a ~28 % decrease. This decreasing trend also holds true for TCs passing within 250 km and 50 km buffers. The proportion of severe TCs (i.e. the number of category 3–5 TCs with respect to the total frequency in their respective periods) has increased from 40 % to 53 % within 250 km, and 45 % to 57 % within 500 km, with only a slight increase noted for the 50 km buffer (38 % to 39 %).

Distinct differences in the mean TC intensities between the two periods, are demonstrated by the boxplots (Figure 3b). The severity (i.e. mean TC wind speed) of TCs passing within 500 km and 250 km of Vanuatu has increased by ~15 % (and ~3 % within 50 km) in the latter period. The recent occurrence of events such as severe TC Pam (2015), TC Keni (2018) and TC Harold (2020) exemplify these increases in intensity, noting also that these analyses were undertaken prior to the occurrence of severe TC Judy and TC Kevin in March 2023.

Care must be exercised when interpreting the intensity changes as data inhomogeneities in the earlier period can limit their usefulness for climate analysis (e.g. [36, 37]). Nonetheless, the globally increasing trend in the proportion of severe TCs (winds ≥ 64 kt) relative to the total number is also supported by Kossin *et al.* [38].

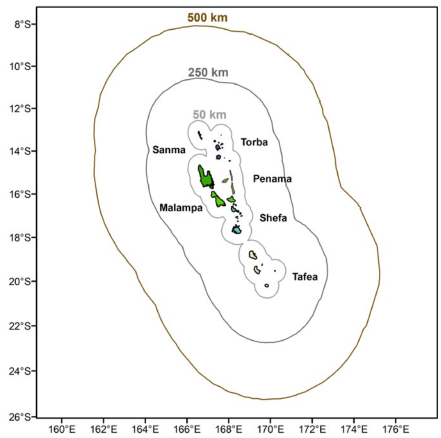
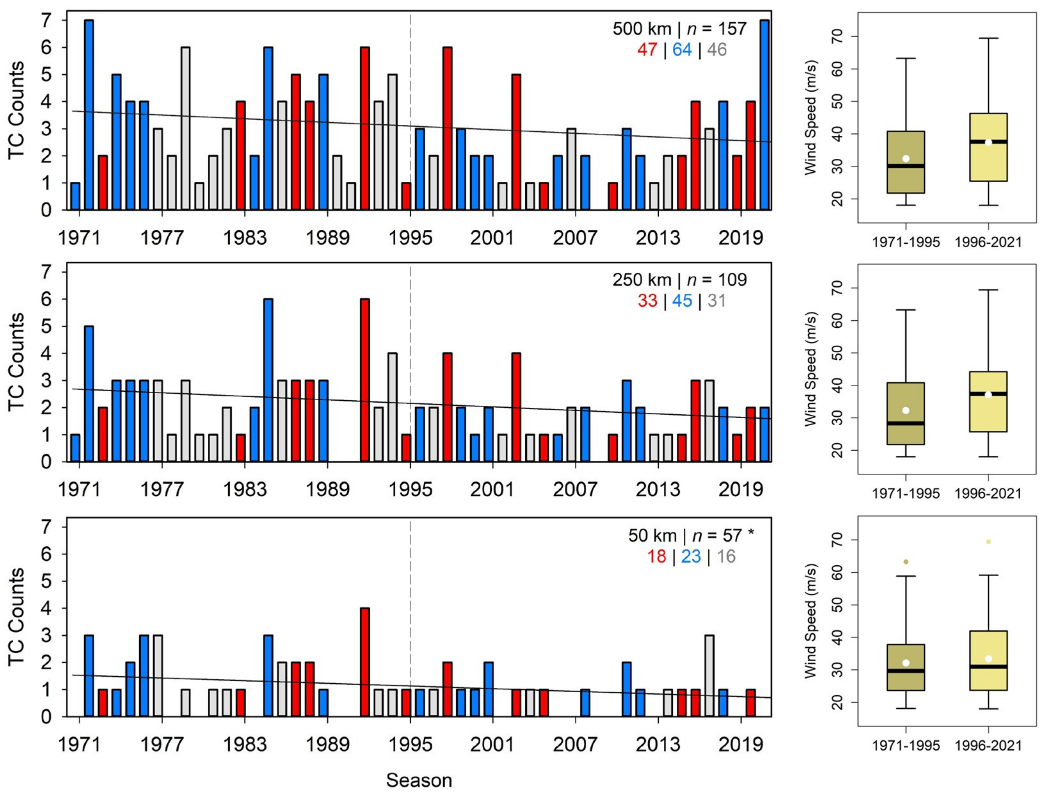


Figure 3 (a) The three buffers (50 km, 250 km, and 500 km) constructed around Vanuatu to extract TC tracks. (b) The observed number of cyclones categorised into El Niño (red), La Niña (blue) and ENSO neutral (grey), that have occurred within 500 km (top row), 250 km (middle row) and 50 km (bottom row) of Vanuatu between the 1971 and 2021 TC season. The total number of TCs within each panel is represented by n, disaggregated into El Niño (red font), La Niña (blue font) and neutral (grey font). The vertical dotted line separates the first period (1971–1995) from the second period (1996–2021). The black line within the timeseries represents the linear trend, which is statistically significant at 90 % confidence level within the 50 km buffer, denoted by an asterisk (*). Also presented (right panel) are their wind speed distributions as boxplots for the two periods analysed. The black line within the boxplot represents the median, the white dot represents the mean, the box is the 25–75th percentile range, and the whiskers represent the 5–95th percentile range.



Observed tropical cyclones and extreme rainfall

Along with destructive winds, TCs are known to bring torrential rainfall, often leading to major river flows and severe flooding. Reports have shown that 15 % of the annual rainfall in Vanuatu is associated with TCs [39].

For Vanuatu, the fractional contributions of TCs to 1- , 2- and 3-day maximum daily rainfall for November–April are 31.2 %, 34.6 % and 35.0 %, respectively. Non-cyclone weather systems are responsible for the remaining 65–68 % of heavy rainfall events. Vanuatu's cyclone-related rainfall amount has increased by about 20 mm/day during 1994–2018 compared with 1970–1993 Figure 4.

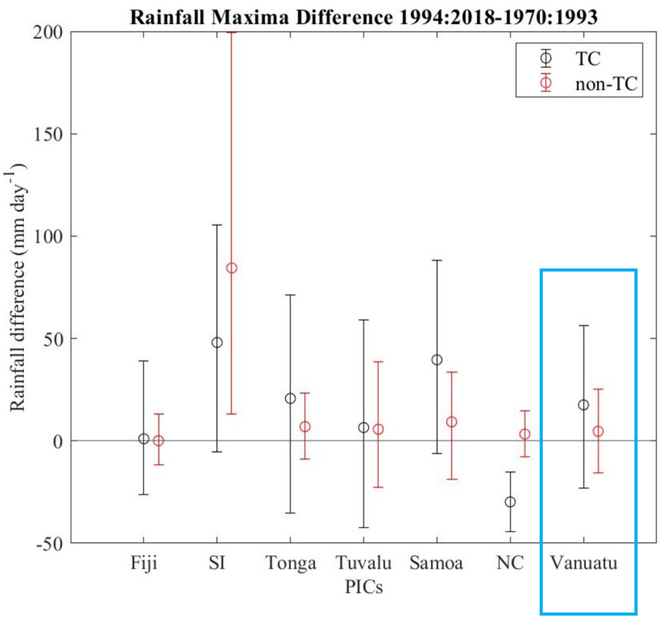


Figure 4 Difference in mean seasonal maximum daily rainfall for Vanuatu (within the blue box) associated with TCs and non-TCs between 1994–2018 and 1970–1993 (Source: Deo et al. [3]).

Observed tropical cyclones and ENSO

The El Niño Southern Oscillation (ENSO) has a strong influence on year-to-year variability in cyclone activity as it affects the position of the South Pacific Convergence Zone (SPCZ) [41]. The SPCZ is a diagonal band of intense rainfall and deep atmospheric convection extending from the equator to the sub-tropical South Pacific [42]. During El Niño events, fewer cyclones occur near Vanuatu because the SPCZ moves north-east. During La Niña events, more cyclones occur near Vanuatu because the SPCZ moves south-west [6].

Cyclones extracted within the three buffers (Figure 3) were also stratified into ENSO phases [43]. The ENSO phases were characterised using the sea surface temperature anomalies (SSTA) over the Niño 3.4 region in the central tropical Pacific. The sea surface temperature is based on the Extended Reconstructed Sea Surface Temperature Version 5 (ERSSTv5; [44, 45]). The SSTAs were calculated relative to the 1981–2010 climatological baseline and averaged over the typical TC season, i.e. November–April. An SSTA above +0.5 °C defines the El Niño phase, an SSTA below –0.5 °C defines the La Niña phase, while SSTAs occurring between these thresholds are classified as ENSO neutral [41].

Vanuatu is more susceptible to TCs during La Niña years than El Niño years (Figure 3b). For instance, between the 1971 and 2021 seasons, TCs within 500 km of Vanuatu were more frequent during La Niña years (~13 cyclones per decade) than El Niño and ENSO neutral years (~9 cyclones per decade) (Figure 3b, top row). A similar tendency occurs for TCs within the 250 km and 50 km buffers, with more TCs during La Niña years (Figure 3b, bottom row) [1].

Several studies have reported an increasing trend in TCs over Vanuatu during the La Niña years. However, these studies were focused on the wider South Pacific region and/or have used different approaches and datasets (e.g. [36, 43, 46, 47]).

Observed cyclone impacts affecting Vanuatu: some recent examples.

Tropical Cyclone Pam in 2015 was the second-most intense TC on record for the South Pacific. It passed directly over Vanuatu as a Category 5 system and was the strongest to affect Vanuatu in the past 40 years. It caused 15 fatalities, displaced 65,000 people, and damaged or destroyed 17,000 buildings, with economic loss and damage totalling VT 48.6 billion (equivalent to 64 % of GDP in 2015). Of this, VT 29.3 billion was attributable to damage and VT 19.3 billion was attributable to loss.

The breakdown of economic loss and damage is provided in the table below. Analysis showed that 69 % of the disaster effects fell within private enterprises and individual ownership, while the remaining 31 % of effects were within public sector ownership.

The cyclone seriously harmed the livelihoods of over 40,000 households, resulting in losses of around VT 1.6 billion in personal income. Low-income individuals and those depending on subsistence livelihoods suffered the most due to reduced incomes and food sources. Crops were destroyed, and the livelihoods of at least 80 % of Vanuatu's rural population were compromised. There were significant losses to ecosystem services. Total recovery and reconstruction costs were estimated at VT 34.1 billion [21].

Tropical Cyclone Pam 2015	
Economic loss and damage	
Total	VT 46.6 billion (64% of GDP)
Economic loss	
Agriculture	33 %
Tourism	26 %
Economic damage	
Housing	32 %
Tourism	20 % *
Education	13 %
Transport	10 %
Recovery and reconstruction cost	
Total	VT 34.1 billion

Tropical Cyclone Harold in 2020 passed directly over Vanuatu and south of Fiji at Category 5 intensity. It temporarily displaced over 18,000 people who took shelter in over 270 evacuation centres. Among the groups most affected were people with disabilities and female- headed households. Over 26,000 households or 129,000 people were impacted, which is approximately 43 % of the population.

Over 218,000 agricultural plants were destroyed, with an economic cost of over VT 13 billion. Damage to various sectors is shown in the table below. Damage to infrastructure and assets cost over VT 27 billion. The economic loss was almost VT 24 billion, including VT 18 billion for agriculture. The compound nature of TC Harold and COVID-19 intensified the scale and broadened the scope of the social, economic, and environmental impacts [26].

Tropical Cyclone Harold 2020	
Damage to housing	
Number of houses damaged	21,000
Number of houses destroyed	>5,000
Damage to natural ecosystems	
Affected area of tropical forests	2,196 km²
Affected area of coral reefs	65.4 km²
Affected area of mangroves	7.8 km²
Affected area of seagrass	11.2 km²
Economic damage	
Health and education	VT 8 billion
Roads, bridges and airports	VT 3 billion
Water facilities	VT 2 billion
Private infrastructure and assets	VT 2 billion

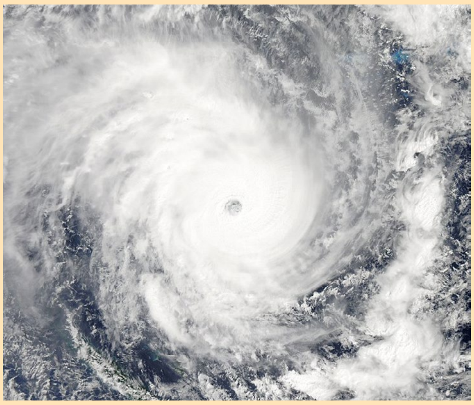


Figure 5 TC Pam (left). Damage caused by TC Harold (right)

Projected changes in tropical cyclones

Projected changes in tropical cyclone frequency and intensity

Understanding the future behaviour of TCs in the Pacific is technically challenging due to the dynamic nature of the underlying drivers, the limitations of historical data, and the inherent uncertainty in the ability of climate models to simulate both frequency and intensity with reasonable confidence over multi-decadal (i.e. climate change) timescales [6]. However, substantial evidence shows that large-scale environmental conditions supporting TC activity have changed significantly due to increasing greenhouse gas emissions [4].

Ongoing increases in greenhouse gas emissions is projected to lead to decreases in the average number of cyclones (low-to-medium confidence) [4, 48]; however, increases are projected in the proportion of severe cyclones and associated wind gusts, storm surges (medium confidence), and extreme rainfall (high confidence) [4, 6]. Consequently, impacts due to severe cyclones are likely to increase in future (medium-high confidence) [7]. This has implications for planning and investment in adaptation strategies that build resilience.

Projections for cyclones in Vanuatu reported here have been conducted using a range of cyclone modelling techniques:

- The 'synthetic tracks' method [49-51] can be used to simulate large populations of TC events for a particular climate and location, given information about the large-scale environment in which the TCs are embedded (e.g. SST, humidity, and vertical wind shear). One advantage of this technique over other climate modelling methods is the low computational cost, so that many thousands of events can be simulated to assess risk at a given location. Another advantage is the very high spatial resolution of the model which can simulate the full intensity distribution of TCs, including the most damaging Category 5 storms.
- Consolidation of climate model data from the Coupled Model Intercomparison Project phase 5 (CMIP5) to produce projections under different greenhouse gas emissions scenarios, e.g. a high emissions scenario (Representative Concentration Pathway 8.5 [RCP8.5]) [1]. This method utilises TCs detected and tracked from several CMIP5 models using the Okubo-Weiss-Zeta (OWZ) scheme [8, 52] to demonstrate TC impacts at the country and provincial levels. The OWZ method assesses the broad environmental conditions suitable for cyclone formation. Several measures were undertaken to address the drawbacks associated with the OWZ outputs [1, 48], such as statistical calibration [53] and selection of best-performing models [8] at the regional level.

Both methods found that the frequency of cyclones affecting the Vanuatu region is projected to decrease slightly. One study [1] indicated ~12 % decrease in the overall frequency of TCs within 500 km of Vanuatu by the end of the century (2070–2100, under RCP8.5) relative to historical climate conditions (1970–2000). Projections derived from the other two buffers (50 km and 250 km) revealed similar trends. A reduction of up to one cyclone per decade was projected by the end of the century, with higher reductions in the northern region (Figure 6) [2]. This reduction in cyclone frequency is consistent with projections based on different cyclone modelling techniques for the broader South Pacific region [4, 52].

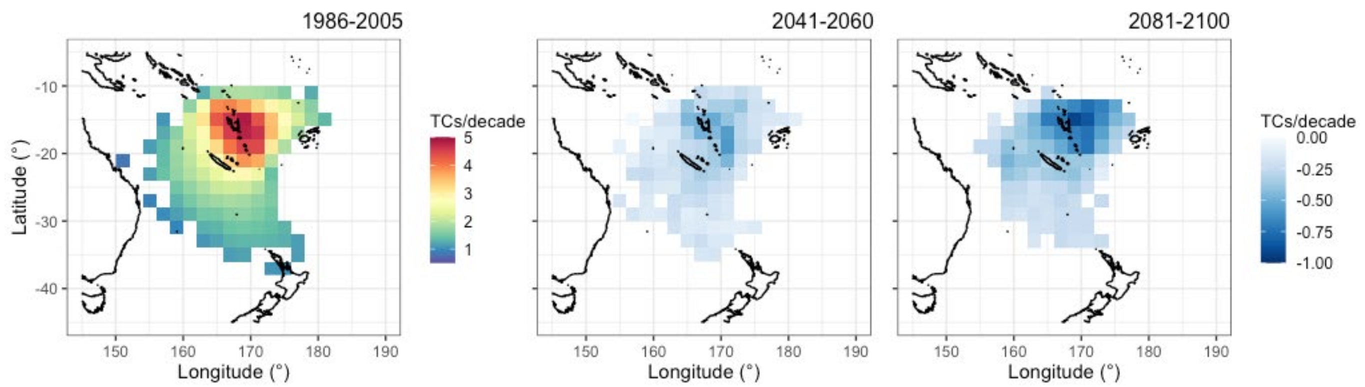


Figure 6 Average number of tropical cyclones (TCs) for the historical period (1986–2005, left panel), and the projected change in the number of cyclones by mid-century (2041–2060, central panel) and late-century (2081–2100, right panel) under RCP8.5 (see Emission pathways factsheet). These data are based on the MIT synthetic cyclone tracks model driven by a set of eight CMIP5 global climate models. Note the cyclone trend per decade scale is negative [2].

A decrease in the frequency of different categories of cyclones is projected, based on the synthetic track analysis (Figure 7) [2]. This is consistent with results based on different TC modelling techniques for the broader South Pacific region [4]. A recent assessment [4] shows a decrease in Category 4–5 TCs for the SW Pacific region, although with large uncertainty.

Regarding cyclone intensity, the synthetic track projections indicate a slight decrease (~2 %) in the mean maximum wind speed of TCs that pass within 50 km of Vanuatu between the historical (1986–2005) and late 21st century (2081–2100) periods, although there is large uncertainty, with half the models indicating an increase and the other showing a decrease. The proportion of severe TCs shows little overall change (< 0.5 %) between the two periods according to the synthetic track intensity analysis, although 5 of 8 models indicate an increased proportion.

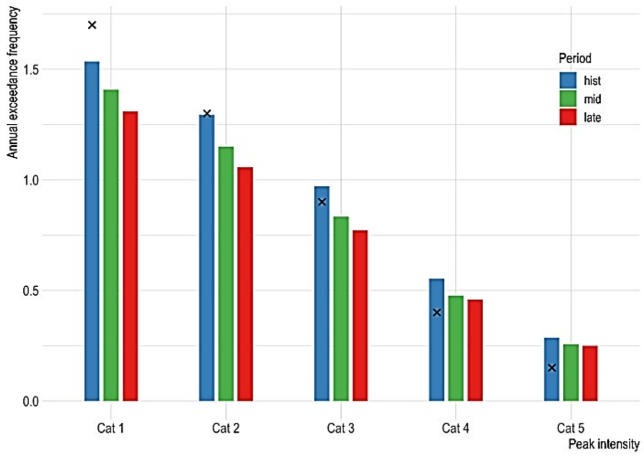


Figure 7 The modelled annual exceedance frequencies for different TC intensity categories (Category 1 to 5) over three periods ("hist": 1986–2005, "mid": 2041–2060, and "late": 2081–2100) for Vanuatu, based on MIT synthetic track analysis. The "x" symbols show the observed exceedance frequencies for the historical period 1986–2005. The annual exceedance frequency here is the probability that at least one TC at a given intensity will occur in any given year. The bars suggest that the chance of a Category 1 event is high, while the chance of a Category 5 event is low, and there is a projected decline in the annual likelihood of all TC intensities.

Using the OWZ method to assess TC intensity [1], a small increase in the mean wind speed intensity is projected by 2070–2100 relative to 1970–2000 periods across all six provinces of Vanuatu (Figure 8) [1]. Malampa, which is centrally located within Vanuatu, exhibits the maximum projected change of 3.2 %, followed by Shefa (2.4 %), Penama (1.7 %), Torba (1.4 %), Tafea (1.2 %) and Sanma with the lowest change of 0.4 %.

The intensity-frequency curves in Figure 8 show an increase in the intensity of severe cyclone wind speeds derived for 10-, 50- and 100-year return periods. For example, the intensity increases by 2–6 % for wind speeds with a 100-year return period. This has implications for future cyclone risk management strategies, especially where the main cities are located – e.g. Port Vila and Luganville within Shefa and Sanma, respectively [1] (Figure 8).

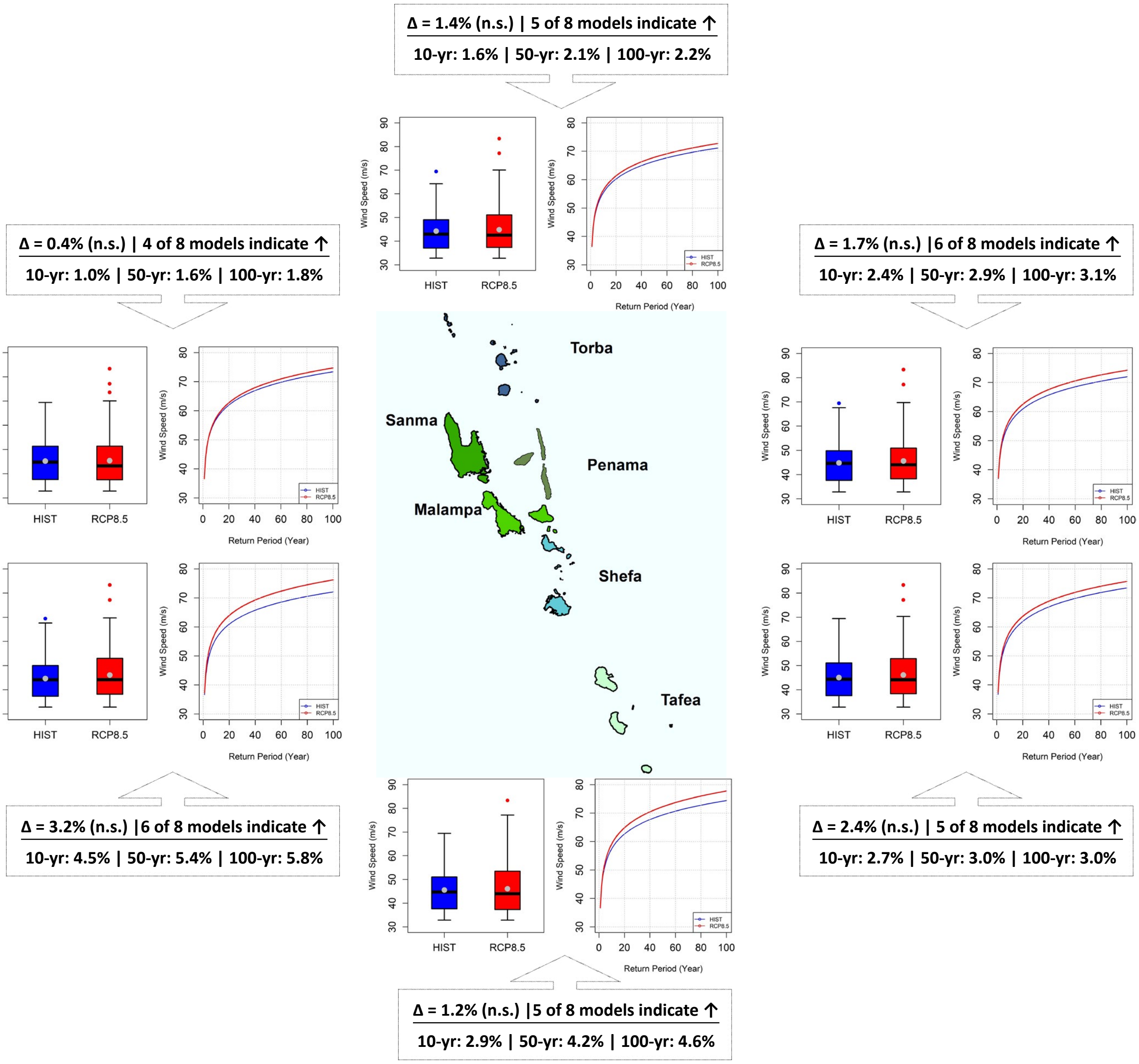


Figure 8 Historical (1970–2000) and projected (2070–2100; high emissions RCP8.5) severe cyclone wind speed (m/s) and intensity-frequency curves for the six Vanuatu provinces within a 500 km buffer. Severe cyclones are defined as category 3–5. Boxplots indicate the distribution of maximum wind speed. The black line within the boxplot represents the median, the white dot represents the mean, the box is the 25–75th percentile range, and the whiskers represent the 5–95th percentile range. For each province, the average per cent change in mean wind speed is noted, as well as climate model consensus information, with 'n.s.' indicating a change that is not statistically significant. Also included is the percentage change in wind speeds for events with 10, 50 and 100-year return periods, derived from the intensity-frequency curves (below dotted lines). Projections are derived from eight climate models following Chand et al. [36] and Bell et al. [37]. (See Extreme rain and wind report for more detailed information). Source: [1].

Tropical cyclones and extreme rainfall in future

In the south-west Pacific, the TC rainfall rate is projected to increase by 0–15 %, with a median increase of ~8 %, due to a 2 °C global warming [4]. However, the variability between climate model projections can be large, particularly for the south-west Pacific basin [6]. Using the synthetic tracks method, the likelihood of a TC Pam rain event (i.e. ~600 mm of accumulated rainfall) occurring at Port Vila, increased 3-fold between 1986–2005 and 2081–2100 for RCP8.5 (Figure 9) [2]. This increase in the rain rate per TC is in agreement with other TC climate change assessments [5].

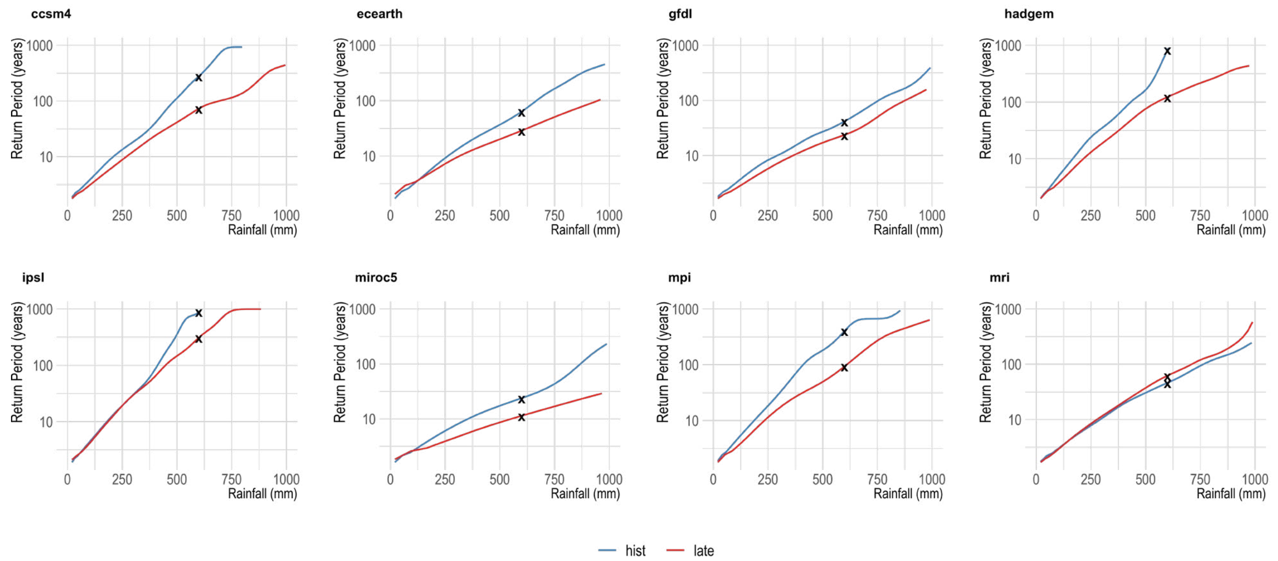


Figure 9 Return periods for accumulated TC-rainfall at Port Vila from the MIT synthetic tracks model, derived from 8 climate models for the historical period (1986–2005, red) and the late 21st century (2081–2100, blue) for RCP8.5 [2]. Black 'x' marks 600 mm of accumulated rainfall to assist visualisation of changes in return periods.

Tropical cyclones and ENSO in future

ENSO will continue to be a dominant large-scale climate process influencing the natural variability of TCs in future. While overall TC frequency is projected to decrease (Figure 10a), TCs are projected to become ~20–40 % more frequent in the entire central Pacific region during future climate El Niño periods than present climate El Niño periods (Figure 10b), and less frequent during future climate La Niña and neutral periods than present climate La Niña periods (Figure 10c) [8] (low-medium confidence). There may be more extreme El Niños and more extreme La Niñas in future [9, 10] (medium confidence). However, observational records show a "La Niña-like" strengthening of the east-west SST gradient over the past century, whereas most climate model simulations project "El Niño-like" weakening of the gradient [54]. This is why a more detailed evaluation of climate model performance needs to be undertaken, especially for TCs [8], with the best performing models used for TC projections.

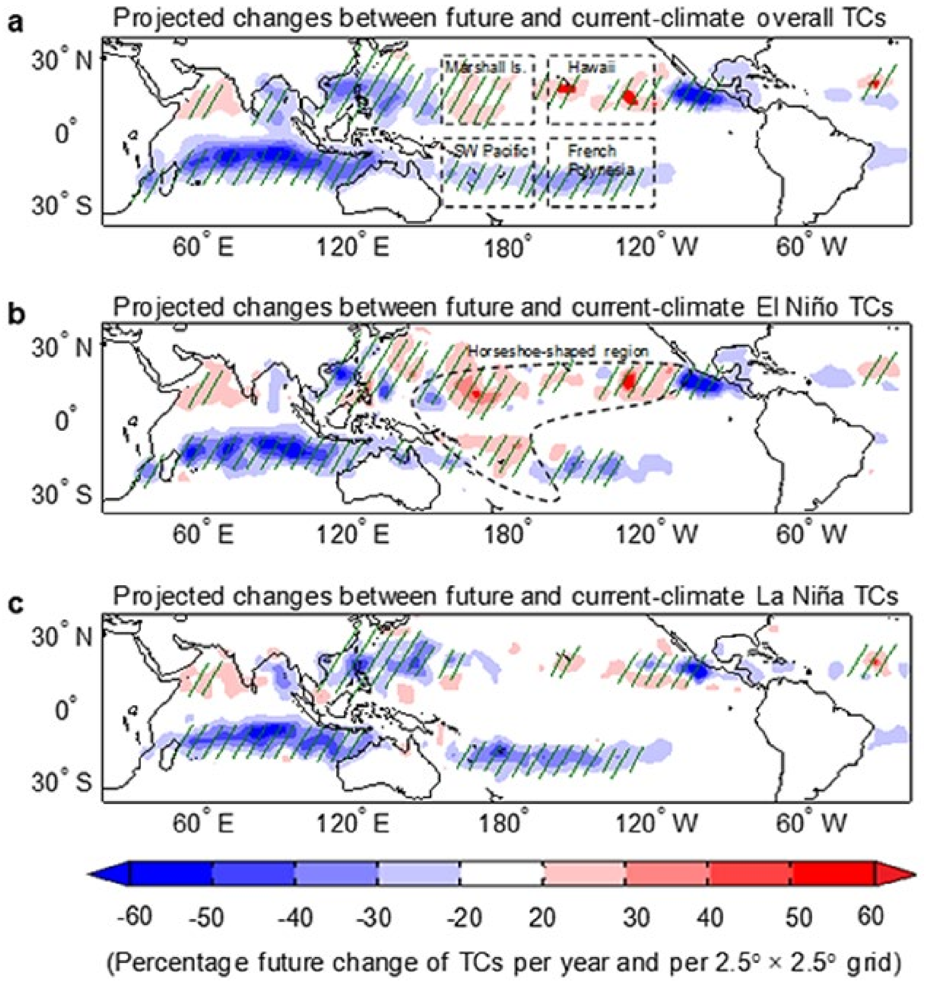


Figure 10 Changes in TC frequency for late 21st century (2070–2100) vs late 20th century (1970–2000) overall (top), for El Niño conditions (middle) and La Niña conditions (bottom). Blue indicates decrease while red indicates increase. Projections are derived from 13 CMIP5 global climate models driven by a high emissions pathway (RCP8.5). Source: Chand et al. [36].

Tropical cyclone return periods

For any TC in Vanuatu with a given maximum wind speed, its return period can be estimated using the intensity-frequency curve in Figure 8. Table 2 presents the return periods of well-known TC events that devastated much of Vanuatu. These return periods are estimates, and the associated probabilities are for a TC exceeding a specific wind speed in any given year. The probability may vary depending on the choice and length of the data set, as well as the approach/methodology used.

The average return period differs between provinces for a given TC event. If we consider, for instance, severe TC Pam (2015, category 5), this event had a ~57-year return period for Shefa and Sanma, ~50-year return period for Tafea, ~68-year return period for Penama and Malampa, and ~77-year return period for Torba in the historical climate (1970–2000). In the future climate (2070–2100 RCP8.5), an event of the same intensity has a ~43-year return period for Shefa, ~35-year return period for Tafea, ~51-year return period for Penama and Malampa, ~49-year return period for Sanma and ~62-year return period for Torba. Overall, the results from Table 2 demonstrate how TC hazards may change towards the end of the 21st century [1].

Table 2 Maximum mean wind speeds of selected severe historical TC events and their corresponding average return periods (years) for historical climate (HIST in blue: 1970–2000) and future climate (RCP8.5 in red: 2070–2100), derived from intensity-frequency curves in Figure 8 for the individual provinces of Vanuatu. Statistics within brackets are the annual probabilities (calculated as the inverse of the return period, e.g. a 1-in-32-year event has a 3.1 % annual probability).

Severe TC event	Maximum mean wind (m/s)	Torba		Sanma		Penama		Malampa		Shefa		Tafea	
		HIST	RCP8.5	HIST	RCP8.5	HIST	RCP8.5	HIST	RCP8.5	HIST	RCP8.5	HIST	RCP8.5
Harold (2020)	63.9	32 (3.1 %)	27 (3.7 %)	26 (3.8 %)	23 (4.3 %)	31 (3.2 %)	24 (4.2 %)	31 (3.2 %)	20 (5.0 %)	26 (3.8 %)	21 (4.8 %)	24 (4.2 %)	18 (5.6 %)
Donna (2017)	56.9	13 (7.7 %)	11 (9.1 %)	10 (10 %)	9 (11.1 %)	11 (9.1 %)	9 (11.1 %)	12 (8.3 %)	8 (12.5 %)	10 (10.0 %)	9 (11.1 %)	9 (11.1 %)	8 (12.5 %)
Pam (2015)	69.4	77 (1.3 %)	62 (1.6 %)	57 (1.8 %)	49 (2.0 %)	68 (1.5 %)	51 (2.0 %)	68 (1.5 %)	41 (2.4 %)	57 (1.8 %)	43 (2.3 %)	50 (2.0 %)	35 (2.9 %)
Ula (2015)	51.4	6 (16.7 %)	5 (20.0 %)	5 (20.0 %)	5 (20.0 %)	5 (20.0 %)	5 (20.0 %)	5 (20.0 %)	4 (25.0 %)	5 (20.0 %)	4 (25.0 %)	5 (20.0 %)	4 (25.0 %)
Jasmine (2012)	54.2	9 (11.1 %)	7 (14.3 %)	7 (14.3 %)	7 (14.3 %)	8 (12.5 %)	6 (16.7 %)	8 (12.5 %)	6 (16.7 %)	7 (14.3 %)	6 (16.7 %)	6 (16.7 %)	5 (20.0 %)

Caveats, uncertainties, confidence, and limitations

Estimating the future behaviour of TCs in the Pacific presents significant technical challenges. This is primarily due to the constantly changing factors that drive TCs, the limitations of historical data, and the inherent uncertainty associated with climate models' ability to accurately simulate both the frequency and intensity of TCs over extended periods (such as multi-decadal timescales influenced by climate change). These limitations are further complicated by the presence of large natural variability [6, 17]. However, undertaking analyses using different techniques can add confidence to the projections (e.g. [1, 2, 4, 52]), noting that selection of climate models should account for how well each model can simulate observed TC features.

Different or conflicting results can also be reported in different experiments because of the different regional buffers used for analysis. For example, one assessment used the Exclusive Economic Zones, which are typically ~370 km from shorelines [22], another used 500 km, 250 km, and 50 km buffers [1], and another [2] used a four-sided polygon bounded by latitudes 21 °S and 12.5 °S, with eastern and western boundaries defined by two lines that intersect circles of radii 200 km centred on Port Vila and Luganville to undertake the synthetic cyclone assessment.

Attribution of observed trends to global warming, such as the increases in Vanuatu's cyclone-induced rainfall, can be difficult [3]. However, substantial evidence shows detectable anthropogenic contributions to increased global average intensity of the strongest TCs since early 1980s and an increase in global proportion of TCs reaching category 4 or 5 intensity in recent decades [54].

It is important to assess the level of confidence in TC projections when communicating results, e.g., Knutson et al. 2020 [4]. The modelling analyses presented here for Vanuatu indicate that TCs are projected to become less frequent in future, for all TC categories, which is consistent with other studies (low-medium confidence). The average wind speed intensity (for explicitly detected TCs) is projected to increase slightly (medium confidence). The projected increase in rainfall associated with TCs is robust (high confidence). Some climate models indicate a poleward shift in TC formation, but there is substantial uncertainty and low-medium confidence.

Recent research indicates the potential for more uncertainty of ENSO projections in climate models, which has implications for regional TC frequency, especially concerning the recent contrast between an observed La Niña-like trend and simulated El Niño-like trends [54]. This divergence likely either reflects an error in the model's climate response, or an underestimate of the multi-decadal internal variability by the models. A better understanding of the fundamental mechanisms of both is needed to reduce the uncertainty [55].

Future planning for tropical cyclone impacts

TCs are associated with:

- Wind impacts causing airborne debris, injuries and deaths, fallen trees, destroyed crops, damaged buildings and infrastructure, and disruption to essential services such as electricity, transport, communication and water. See the Box on Cyclones Pam and Harold.
- Storm surges mainly through strong wind and low central pressure contributions.
- Destructive waves generated by strong winds, even from far-located TCs.
- Coastal flooding through heavy rain, storm surge and destructive waves.
- Riverine flooding due to heavy rain over catchment areas.
- Saltwater intrusion through storm-surge over-wash and coastal flooding.
- Landslides through prolonged periods of heavy rainfall.

The provincial projections demonstrate that increasing TC hazards are likely to be encountered by the end of the 21st century, meaning that relevant agencies may be required to enhance adaptation and planning processes. Although Vanuatu is experienced in responding to cyclones, a double event such as TC Judy and TC Kevin in March 2023 presented unprecedented challenges.

Sea level rise and an increase in extreme sea level events are projected, which may exacerbate cyclone impacts near the coast (medium-high confidence) [1, 4-6]. The extent of the impact may differ within Vanuatu due to multiple factors including, but not limited to, local geographical morphology (e.g. sandy beach vs rocky cliffs), level of exposure to TCs (e.g. assets near the coast), and the adaptive capacity of individual communities [6]. Projected higher sea levels are likely to increase the impacts of storm surges, destructive waves, and coastal inundation. This would increase saltwater intrusion into freshwater aquifers and cultivable land and cause coastal erosion (Figure 11) [6].

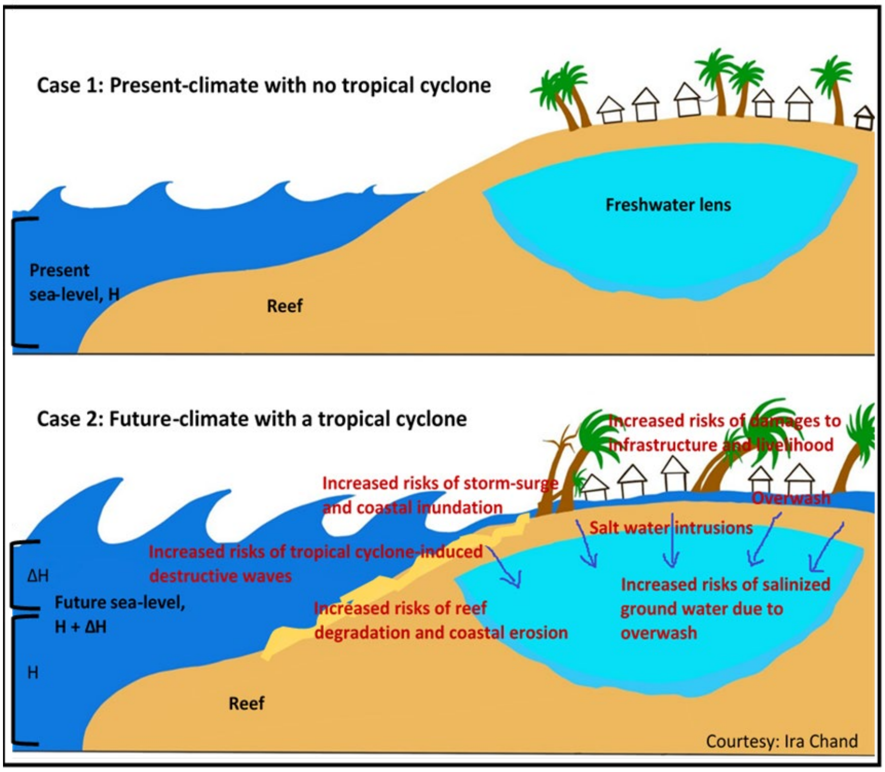


Figure 11 Conceptual diagram of likely changes in tropical cyclone-induced risks in a warming climate for two cases: Case 1 represents a condition in present-climate without any tropical cyclone, and Case 2 represents a likely condition in future climate in the presence of a severe tropical cyclone event and future sea level rise.

Adaptation options include cyclone early warning systems, evacuation centres, community education and awareness-raising activities, insurance premium incentives for resilient buildings, engineering options to increase resilience, e.g. updating the Vanuatu Building Code 2000, and stronger compliance with the Building Code. (See Bungalow design infobyte, TC impacts for agriculture infobyte, and Extreme rainfall impacts on airports infobyte).

After tropical cyclones occur, there is an opportunity to 'build back better', creating more resilient communities by including disaster risk reduction measures to strengthen infrastructure, social services, the economy, and the environment. In the case of TC Harold (2020), this included (1) strengthening public services to implement recovery, (2) strengthening health facilities and preventative/curative health care services, (3) strengthening water, sanitation and hygiene facilities and practices, (4) strengthening education facilities and services, (5) strengthening disaster preparedness, response and recovery mechanisms and structures, (6) supporting self-reliance, (7) promoting and strengthening economic recovery and income generation activities, (8) supporting vulnerable groups and cultural revival, (9) strengthening public and private infrastructure, and (10) strengthening environmental services and resilience [42].

Knowledge gaps and research needs

There are significant uncertainties about projected changes in cyclone frequency, intensity, and formation regions. Further research is required, using methods that are better able to simulate observed cyclone properties. This includes fine-resolution dynamical and statistical downscaling of global climate model simulations, with a focus on hazards that cause significant impacts, such as heavy rainfall, strong winds, and high sea level.

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