Vanuatu's climate: Current and future variability and change

EXPLAINER

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Contents

Summary

This report provides an overview of the climate in Vanuatu:

1. **Climate and weather characteristics:** The South Pacific Convergence Zone (SPCZ) is a diagonal band of intense rainfall and deep atmospheric convection extending from the equator to the subtropical South Pacific. It is the dominant influence on Vanuatu's weather and climate. The region has a warmer and wetter season from November to April, and a slightly cooler and drier season from May to October. While the frequency of tropical cyclones (TCs) affecting Vanuatu varies from year to year, these storms pose greatest risks during November to April.

2. **Climate processes and variability:** In the atmosphere, the dominant influence on rainfall patterns and TC activity is the position and intensity of the SPCZ. In the ocean, processes that affect Vanuatu include currents and areas of upwelling.

   The El Niño Southern Oscillation (ENSO) is the main driver of climate variability in the tropical Pacific due to its influence on ocean temperatures and strong interactions with the atmosphere. For Vanuatu, the El Niño phase of ENSO is typically associated with decreased rainfall, fewer TCs, more drought, cooler sea surface temperatures (SSTs) and lower sea levels. During the La Niña phase, the opposite tends to occur over Vanuatu.

Climate variable	La Niña	El Niño
Rainfall	Wetter	Drier
Drought	Less	More
Tropical cyclones	More	Less
Sea surface temperature	Warmer	Cooler
Sea level	Higher	Lower

3. **Observed climate changes:** Greenhouse warming is already affecting the Vanuatu climate. Annual average temperature of the Vanuatu region (including surrounding ocean) has increased by around 0.7 °C since the pre-industrial period (1850–1900), which is slightly lower than the global average. Sea surface temperatures are increasing, contributing to marine heatwaves becoming warmer and lasting longer. Rainfall extremes have increased slightly since 1951, and interannual variability is large. The 10–15 cm rise in sea level in the western tropical Pacific since 1993 is a pressing concern for the low-lying coastal areas of Vanuatu, which are vulnerable to flooding and erosion. TCs have decreased in frequency since 1971 but have also become more intense.

4. **Projected climate changes:** Projected changes in annual average temperature over the Vanuatu region by 2050 range from 0.5–1.1 °C for a low emissions pathway to 0.8–2.0 °C for a high emissions pathway, relative to the recent past (1986–2005), with likely greater warming over land than ocean. Up to 3 °C or more of regional warming is possible by the end of the century if emissions continue unabated.

   The equatorial Pacific climate is projected to become wetter overall as the ocean warms, however there is uncertainty about future mean rainfall changes around Vanuatu because of opposing climate change mechanisms ("wet gets wetter" versus "warmest gets wetter"). Changes to the latitude of the SPCZ are likely to be the largest determinant of future rainfall change in Vanuatu, with plausible cases of the SPCZ moving south (Vanuatu becomes wetter), small change or moving north (Vanuatu becomes drier). Extreme daily rainfall is likely to become more intense and more frequent. TCs will continue to be a hazard for Vanuatu with the potential for fewer but stronger storms. Extreme droughts may also become more frequent and severe as the climate warms.

   Projected changes in mean sea level by 2050 range from 17–30 cm for a low emissions pathway to 22–37 cm for a high emissions pathway. Global sea level rise could lead to more coastal flooding and erosion in Vanuatu, although vertical land motion (uplift due to earthquakes) may counteract sea level rise in some locations. A 'low likelihood, high impact' outcome of accelerated Antarctic ice sheet and ice cliff disintegration and more rapid sea level rise is possible, especially for higher warming scenarios.

5. **Future climate variability:** Warmer ocean temperatures and changes in atmospheric circulation patterns due to greenhouse gas emissions are projected to lead to increased annual climate variability in the tropical Pacific, including around Vanuatu. Climate models project increased variability of rainfall and storms. While TC occurrence is projected to decrease over the south-west Pacific region, including around Vanuatu, more TCs are projected during future El Niño events compared with historical El Niño conditions, with fewer TCs during future La Niña events. An increase in the variability of SST will translate to an increase in the frequency and magnitude of marine heatwaves. It is likely that greenhouse warming will enhance El Niño related sea level extremes, potentially leading to coastal flooding occurring sooner than expected due to sea level rise alone.

6. **Implications of climate variability and change:** Continued climate changes are likely to exacerbate existing challenges such as food and water insecurity, displacement of coastal communities, and damage to infrastructure and ecosystems. Adaptation strategies such as strengthening infrastructure and building resilience in vulnerable communities can help Vanuatu cope with the impacts of climate change.

Climate and weather characteristics

The 80 island archipelago of Vanuatu is located near the southern boundary of the South Pacific Convergence Zone (SPCZ; Figure 1), which is a band of frequent heavy rainfall extending from near the equator and the Intertropical Convergence Zone (ITCZ) toward the mid-latitudes [1]. The SPCZ is the dominant influence on the regional weather and climate [2]. In the south-western tropical Pacific Ocean, south-easterly winds are common; helping moderate the heat and humidity associated with the warmer ocean closer to the equator. The high sea surface temperatures of the western Pacific warm pool, along with abundant atmospheric moisture (i.e. high humidity), usually translate to sufficient rainfall for Vanuatu's freshwater needs. However, extreme weather events such as heatwaves and droughts, or tropical cyclones (TCs) and prolonged floods, resulting from climate variability can cause considerable damage and loss.

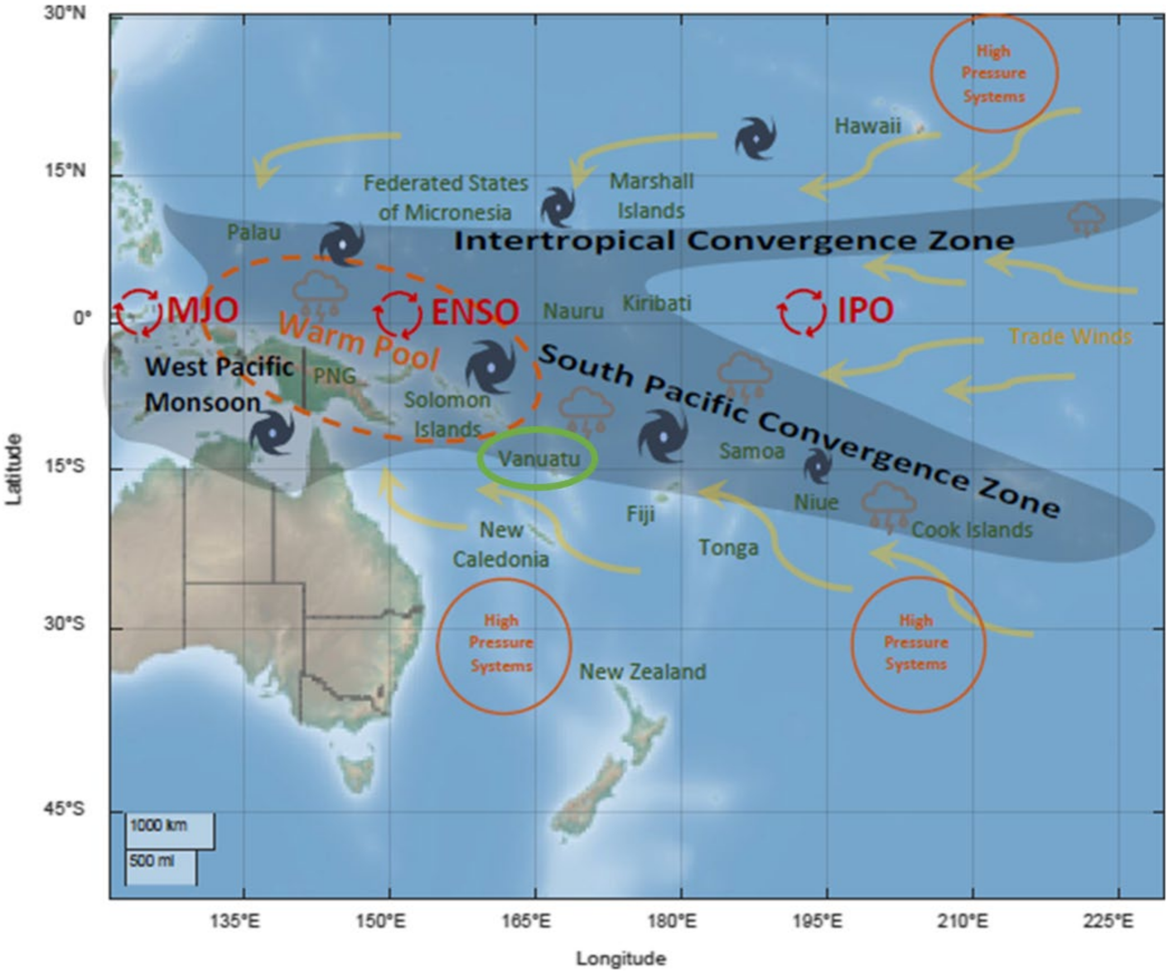

Figure 1 Vanuatu (13 °S–21 °S, 166 °E–171 °E; green circle) is in a region of predominantly south-easterly winds (yellow arrows). Persistent clouds associated with the SPCZ (grey shading) are typically located to the north. The SPCZ is oriented diagonally between the warmest SST in the western tropical Pacific (Warm Pool; dashed circle) and the cooler SST in the south-eastern subtropical Pacific. Other features of the tropical Pacific climate include the Intertropical Convergence Zone (ITCZ), easterly Trade Winds, and regions of usually high atmospheric pressure near the surface (solid orange circles). Three modes of climate variability affect the climate around Vanuatu (MJO, ENSO, and IPO, which are described in this report; circles with arrows). Source: Chand et al. [3].

Temperature and rainfall

Vanuatu experiences a warm climate with most locations having a relatively small seasonal cycle in temperature, but a seasonal distinction between wetter and drier times of year. The annual climate cycle is closely associated with the temperature of the upper ocean [4]. Most of the warmest waters on the planet are in the so-called Warm Pool in the western tropical Pacific Ocean [5] (Figure 2). Here, the SST is warm enough (over 28 °C in the Warm Pool; Figure 2a, b) to sustain strong convection in the atmosphere [6]. Heavy rainfall is common in the Warm Pool because there is abundant atmospheric moisture [7] and uplift driven by converging winds [8], which are necessary ingredients for storms (Figure 2c, d).

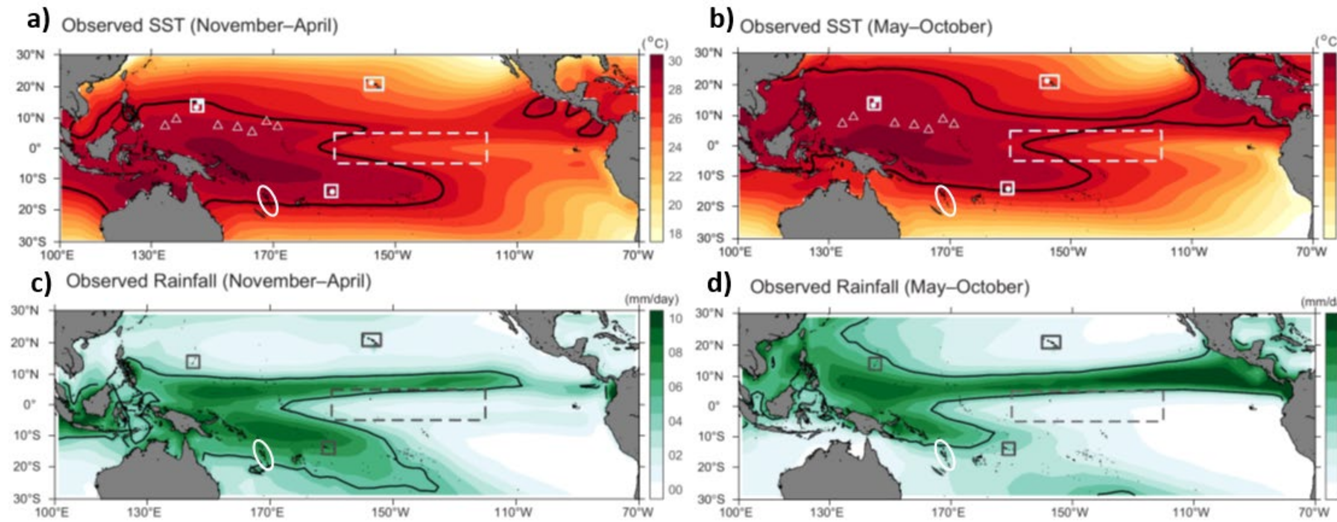

Figure 2 Observed mean SST and rainfall for the tropical Pacific during November–April and May–October, left and right columns, respectively (shadings; see colour bars). SST contour lines (a, b) depict the 28 °C isotherm. Rainfall contour lines depict the 5 mm/day mean isohyet (c, d). The averaging period is 1985–2014. The Vanuatu region is circled, and the dashed rectangle encloses the Niño 3.4 region. Adapted from: Dhage and Widlansky [9].

The tropical Pacific climate is characterised by significant seasonal variations in both SST and rainfall (Figure 2). The observed seasonal mean SST for the region during November–April (Figure 2a) and May–October (Figure 2b) indicates all of Vanuatu being surrounded by the Warm Pool during at least half of the year on average. In northern Vanuatu, the SST is sufficiently warm year round to sustain atmospheric convection (see contour lines). The highest observed rainfall follows the location of the ITCZ and SPCZ (north and south of the equator, respectively), and exhibits a seasonal migration that resembles the movement of the Warm Pool (Figure 2c, d). During November–April, all of Vanuatu is affected by the heaviest band of rainfall (i.e. being within the 5 mm/day mean rainfall contour). During May–October, only northern Vanuatu experiences such heavy rainfall.

In Vanuatu's capital, Port Vila, which is located in the central part of the Archipelago, air temperatures are hotter in November to April than in May to October (Figure 3a). Periods of wet and dry weather are common year-round, but the wet season lasts from November–April, while the dry season is from May–October (Figure 3a). This annual pattern is typical for most of Vanuatu, though the climate of Pekoa, in the north, is a bit warmer and wetter while White Grass airport in the south is slightly cooler and drier, compared to Port Vila (Figure 3b, c)[10].

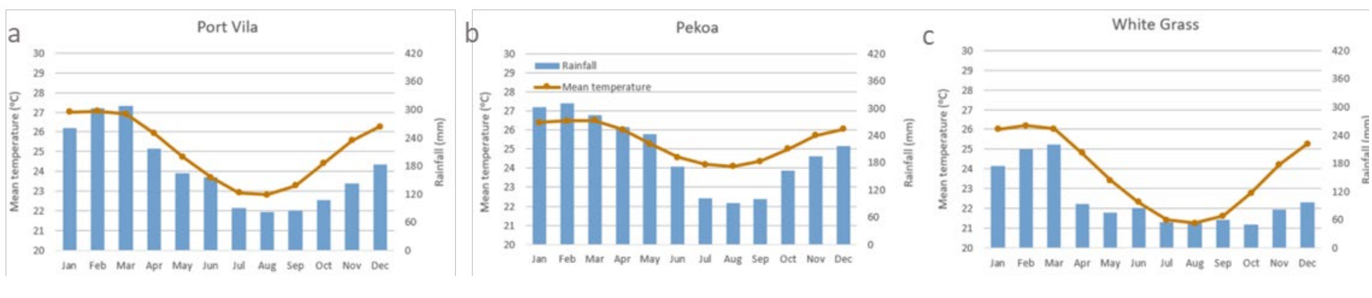

Figure 3 Monthly mean surface air temperature (lines) and rainfall (bars) for Port Vila, Pekoa, and White Grass airport for 1971–2000. Data source: [11]

Extreme rainfall and TCs

Severe storms pose a significant risk to Vanuatu, especially during the warm and wet season (November–April). Warm SSTs support the formation of these storms, which can bring heavy rainfall, strong winds, and storm surges that can result in significant loss and damage [12]. Many TCs form along and south of the SPCZ when circulating warm and moist air masses (referred to as disturbances) generate severe storms [13].

Figure 4 illustrates the occurrence and tracks of TCs passing near Vanuatu. For example, the 2014/2015 season is shown, which includes the track of Severe Category 5 TC Pam which passed over Vanuatu in March 2015. Only one other TC tracked near Vanuatu that season (see box in Figure 4a). The destruction caused by Severe TC Pam is a reminder that it only takes one storm to make a catastrophic season [14].

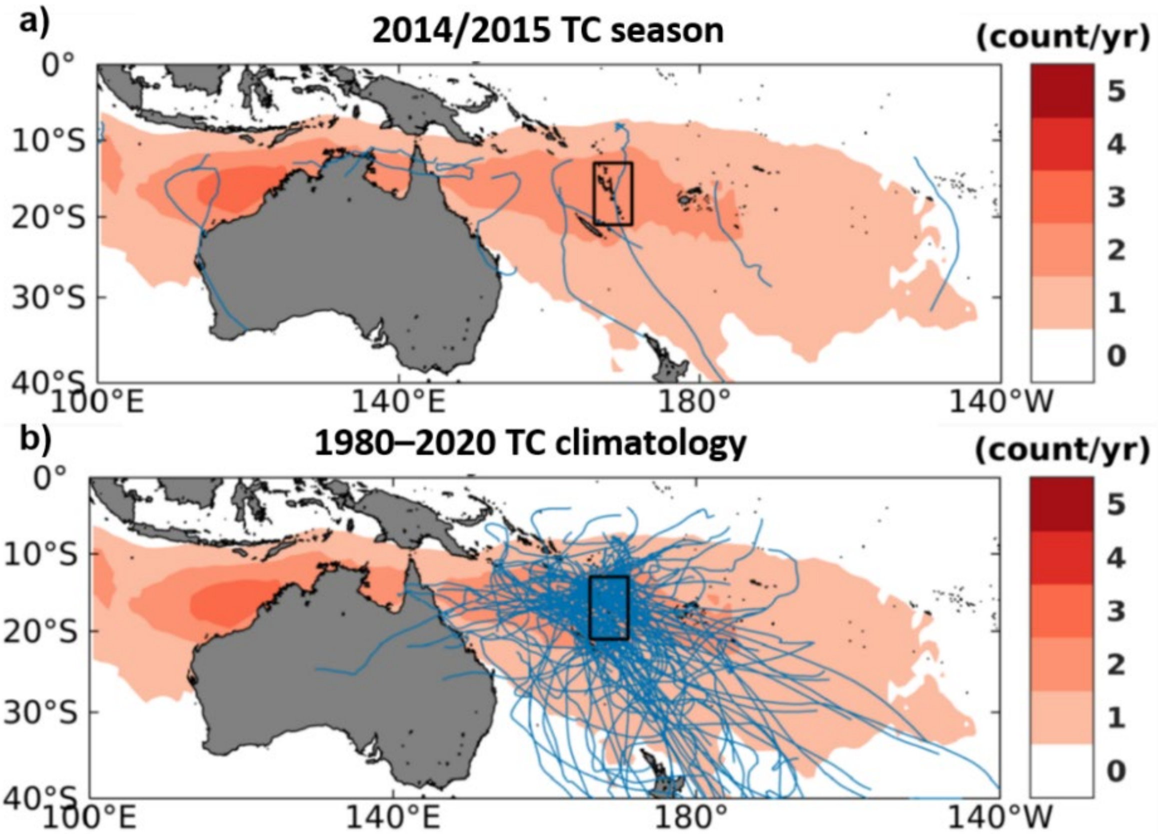

Figure 4 TC occurrence climatology (shading) and tracks (lines). a) 2014/2015 TC season showing the track of the severe TC Pam striking Vanuatu during March 2015. b) Tracks of all TCs during 1980–2020 passing near Vanuatu (box). The density of TC counts is approximately equivalent to the average occurrence of a track within 500 km of a location per year. TC data are from the International Best Track Archive for Climate Stewardship [IBTrACS; 15] and assessed on a 1° x 1° latitude–longitude grid following the methodology in Widlansky et al. 2019 [16].

Weather extremes, including heatwaves, droughts, extreme rainfall, TCs, and storm surges pose significant challenges for risk management. Each of the climate and weather characteristics have unique and potentially profound implications for local communities in Vanuatu. See [Van-KIRAP infobytes] that provide examples of the climate hazard-based impacts.

Climate processes and variability

Important climate processes

The climate of Vanuatu is driven by complex interactions between atmospheric and oceanic processes in the tropical Pacific. In the atmosphere, the dominant influence on the regional climate is the position and intensity of the SPCZ (described above; Figure 1), which affects rainfall patterns [1] and TC activity [13]. In the ocean, processes that affect Vanuatu include currents, such as the North Vanuatu Jet [17], and areas of upwelling [18]. The exchange of heat and freshwater between the atmosphere and ocean is also important. These air-sea interactions can lead to variability in SST, which in turn affect weather patterns and marine ecosystems [19].

The interannual-to-multidecadal variability is illustrated in time series of SST, rainfall, sea surface height (SSH), and local relative sea levels around Vanuatu[1] (Figure 5). These variables are closely correlated in the region around Vanuatu (e.g. the warmer and wetter seasons occur at the same time of year, which is also when the sea level is typically highest). The influence of modes of variability such as the El Niño Southern Oscillation (ENSO) can also be seen in the time series, especially for rainfall (typically drier during El Niño, as discussed below). Understanding this variability is crucial for preparing for climate anomalies and extreme weather events.

The regional climate around Vanuatu is affected by three principal modes of variability that operate on a variety of timescales: the Madden-Julian Oscillation (MJO), ENSO (as introduced above), and the Interdecadal Pacific Oscillation (IPO).

- The MJO affects weather patterns on synoptic-to-intraseasonal timescales (i.e. a few days to a couple of months), and especially influences convective heavy rainfall over the Philippines, Indonesia, Borneo and New Guinea [20]. The MJO also affects the SPCZ region, including Vanuatu [2].
- ENSO is a stronger mode of variability, affecting year-to-year and multi-year climate anomalies in the tropical Pacific and worldwide [e.g. 21]. This important mode of variability is discussed in more detail below.
- The IPO shares many similarities with the effects of ENSO, except that this mode of variability occurs on a much longer timescale [i.e. decades; 22].

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[1]The SSH is measured by satellites, whereas the sea level is measured by a tide gauge stationed on land in Port Vila. Only the tide gauge measures the water level relative to land, which is important for recording coastal sea level conditions. At the Port Vila tide gauge, there is no long-term trend in the sea level measurements (see the next section for description of the observed climate changes).

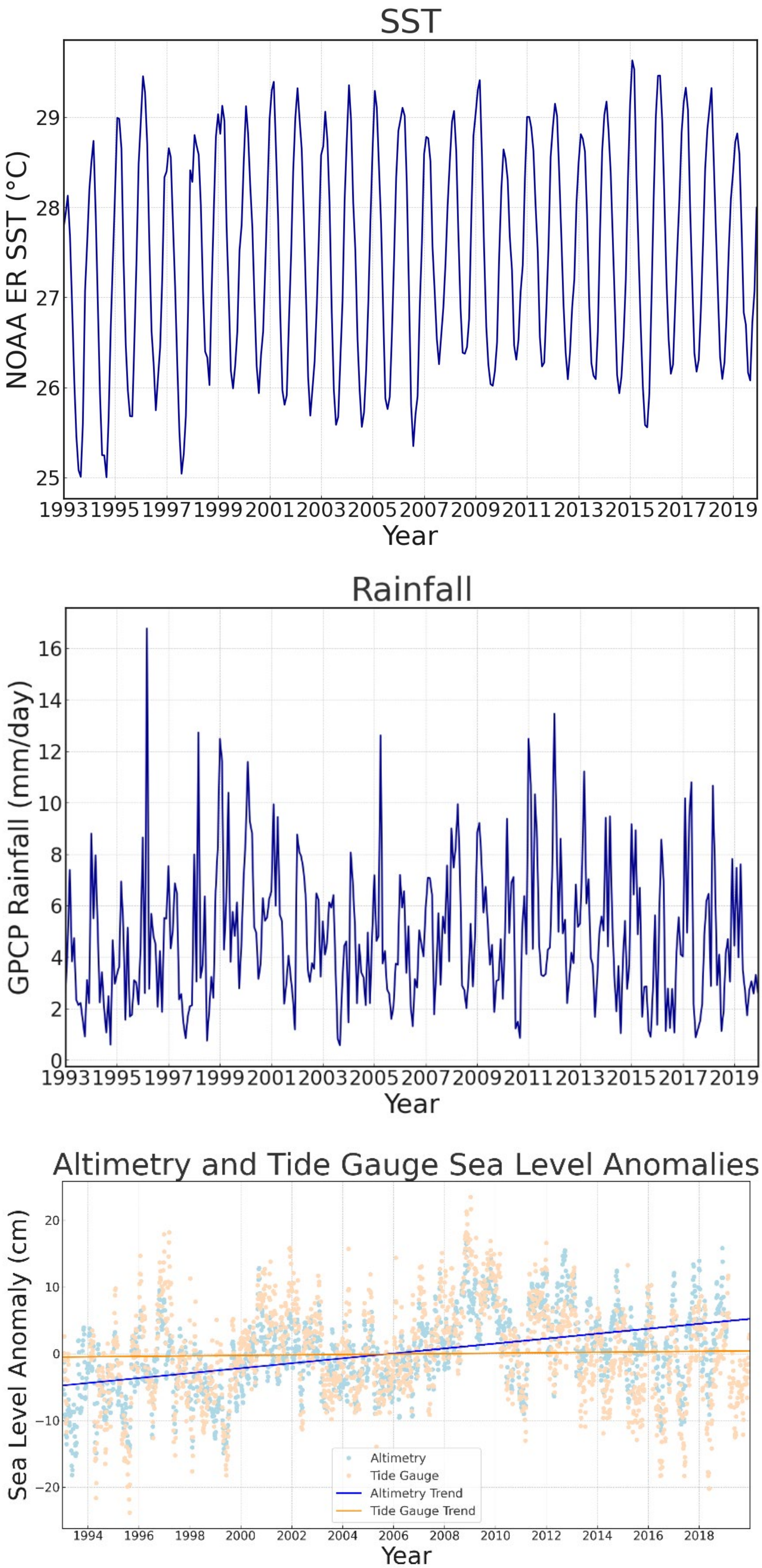

Figure 5 SST (1993–2020) (top), rainfall (1993–2020) (middle), and SSH as well as relative sea level (1993–2020 (bottom) around Vanuatu (13 °S–21 °S, 166 °E–171 °E). Monthly data from the NOAA ER SST and GPCP rainfall data sets, respectively. Daily data for satellite altimetry measured SSH and the tide gauge measured relative sea level, viewed using the Sea Level Explorer Tool (https://ccar.colorado.edu/altimetry/).

ENSO related climate variability

ENSO is a natural climate phenomenon that occurs across the tropical Pacific and affects weather patterns around the world, including Vanuatu. There are three phases of ENSO; El Niño, Neutral, and La Niña, with the El Niño and La Niña phases illustrated in Figure 6. El Niño events usually occur every 3–7 years, typically peaking during December or January and lasting for less than one year [e.g. 23]. El Niño is often followed the next year by a La Niña event [e.g. 24]. La Niña conditions typically persist longer than El Niño, and there have been three so-called triple-dip La Niña events (lasting three years) since 1970. The most recent triple-dip La Niña event ended around February 2023, and it was associated with prolonged warm and wet conditions in the western tropical Pacific as well as prolonged high sea level anomalies around Vanuatu [25].

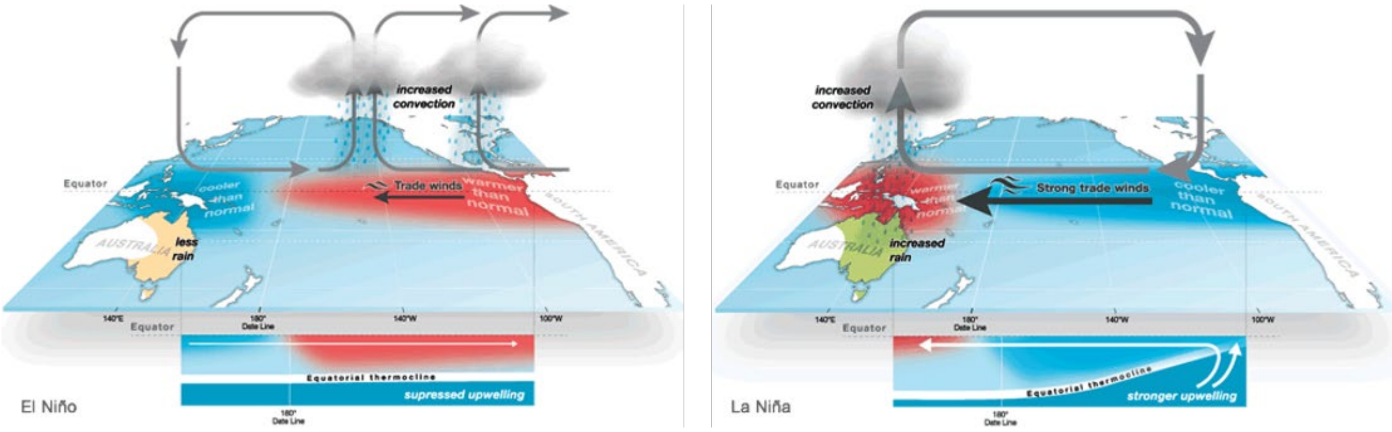

Figure 6 During El Niño (left), trade winds weaken (or reverse) allowing the Warm Pool to shift east, causing the ocean to cool near Vanuatu. During La Niña (right), enhanced trade winds strengthen the Warm Pool in its typical location north of Vanuatu. Image source: Australian Bureau of Meteorology (http://www.bom.gov.au/climate/about/?bookmark=enso).

ENSO is measured using several types of climate indices, which usually are based on measurements of the SST variability in the central equatorial Pacific. The Oceanic Niño Index (ONI; Figure 7) is a widely used metric because it quantifies the monthly average SST in the Niño 3.4 region (5 °N–5 °S, 120–170 °W; see Figure 8) with respect to a 30-year climatology that is updated every five years, which is done to account for the long-term warming trend. When the ONI is positive (i.e. above-normal SST), El Niño conditions are typical, whereas negative ONI is associated with La Niña. Another common ENSO index is the Southern Oscillation Index (SOI), which measures the atmospheric sea level pressure differences between Tahiti (French Polynesia) and Darwin (Australia).

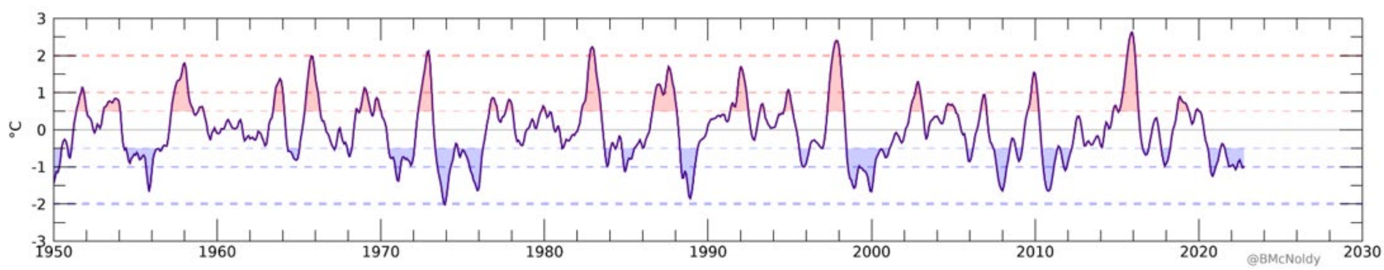

Figure 7 The phase of ENSO as defined by the ONI. El Niño or La Niña conditions are common when the ONI exceeds ± 0.5 °C, which are indicated by red and blue shadings, respectively. Anomalies during 2011–2021 are with respect to the 1991–2020 monthly average SST (an earlier climatology is used to calculate previous anomalies). Image source: Brian McNoldy, University of Miami (https://bmcnoldy.rsmas.miami.edu/tropics/oni/).

Regional differences in climate variability

The magnitude of climate variability is not uniform throughout the tropical Pacific. The regional variation in interannual standard deviation (a measure of variability) of SST, rainfall, and SSH is illustrated in Figure 8 (a, c, and e). Larger standard deviations for SST occur in the equatorial central and eastern Pacific, notably in the Niño 3.4 region (Figure 8a). The rainfall variability is also relatively large near the Niño 3.4 region, as well as throughout the major rainfall bands in the tropical Pacific (i.e. the ITCZ and SPCZ), which includes around Vanuatu (Figure 8b). The wide expanse of larger rainfall variability (standard deviations exceeding 1 mm/day) is primarily a consequence of ENSO having a substantial and wide-ranging influence on the tropical Pacific climate. Sea level variability associated with ENSO is likewise largest near the equatorial central Pacific and in the western Pacific (Figure 8c). For Vanuatu, the sea level variability is greatest in the north (standard deviations exceeding 10 cm), and about half as much in the south.

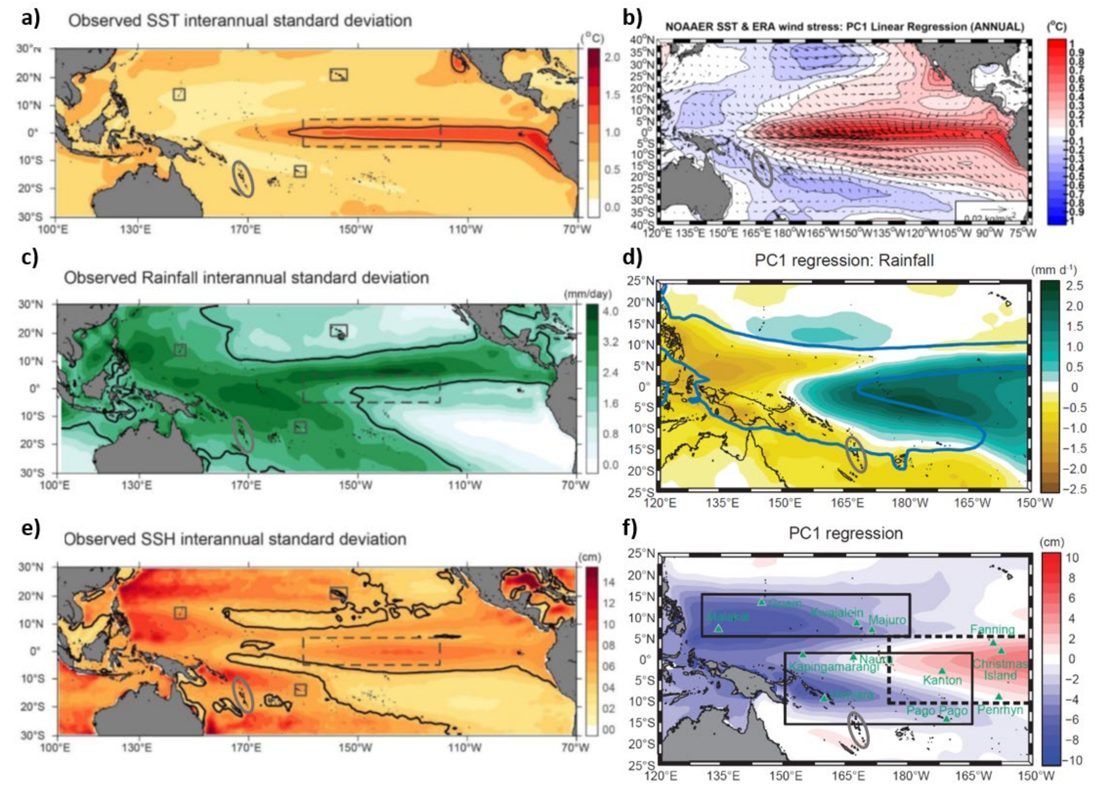

Figure 8 Interannual climate variability associated with ENSO. (a, c, and e) Standard deviation of monthly anomalies of SST (°C), rainfall (mm/day), and SSH (cm). (b, d, and f) Linear regressions of these variables associated with the leading pattern of SST variability (i.e. the first principal component; PC1, which is the leading mode of interannual variability). Vanuatu is circled in each map and the Niño 3.4 region is boxed in a, c, and e. Sources: Dhage and Widlansky 2022 [9], Widlansky et al. 2014 [26]

Climate anomalies typical of El Niño events for SST (also winds), rainfall, and SSH are illustrated in the right column of Figure 8 (b, d, and f). During El Niño, positive anomalies of SST, rainfall, and SSH are most pronounced in the central tropical Pacific. For most of the western Pacific including around Vanuatu, however, El Niño is associated with somewhat cooler and drier conditions. The opposite anomalies are typical during La Niña, although for SSH there is usually a larger anomaly around Vanuatu, compared to during El Niño. The prolonged high sea level anomalies during 2020–2023 in the western tropical Pacific were a manifestation of La Niña [27].

In summary, for Vanuatu, El Niño events tend to bring drier conditions (Table 1), as well as a late start to the wet season and cooler than normal dry seasons. The opposite occurs during La Niña events, where Vanuatu experiences wetter conditions and an earlier start to the wet season. ENSO also affects the genesis and tracks of TCs worldwide, including around Vanuatu. While the number of TCs affecting Vanuatu varies widely from year-to-year, with none in some seasons but up to six in others [13], El Niño events typically bring fewer TCs, whereas TCs are more common during La Niña events [28]. Regarding sea level, as noted earlier, above normal (below normal) anomalies are typical during La Niña (El Niño). Above normal sea levels during La Niña can lead to coastal flooding because high sea levels exacerbate storm surges or extremely high tides [29, 30]. Above normal sea levels were observed during the prolonged 2020–2023 La Niña event [25].

Table 1 Summary of ENSO influences for Vanuatu.

Climate variable	La Niña	El Niño
Rainfall	Wetter	Drier
Drought	Less	More
TCs	More	Less
SST	Warmer	Cooler
SSH and local sea level	Higher	Lower

Observed climate changes

Vanuatu is experiencing changes in its climate and weather patterns, which are already having major impacts on the country's environment, economy, and society. Ocean and air temperatures have been rising, and while there has not been much long-term change in average rainfall, fewer but strengthening TCs have been observed, as has a rising sea surface height (SSH).

Temperature and rainfall

The Vanuatu region has warmed by around 0.7 °C since the pre-industrial period (1850–1900) [31], however there is no clear trend in total rainfall for Vanuatu (Figure 5)[10]. There is evidence of extreme daily and sub-daily rainfall becoming more common in recent years [10, 32] (i.e. on timescales much shorter than for the monthly anomalies shown in Figure 5), which is expected in part because the warmer atmosphere can hold more moisture [33]. Other factors, such as the intensity of the storms bringing rainfall may also contribute to trends in short-duration rainfall. Droughts are also becoming more impactful as the temperature warms and enhances evapotranspiration, which dries the surface of soil and plants [34].

Extreme rainfall and TCs

The total number of TCs has declined since 1971 (Figure 9). 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 [28]. This 28 % decrease is not statistically significant. The proportion of severe TCs (i.e. the number of severe TCs within 500 km with respect to the total occurrence in their respective periods) has increased from 45 % to 57 % [28].

Distinct differences in the mean TC severity between the two periods (1971–1995 versus 1996–2021) are shown in Figure 9 (right). The severity, as indicated by the mean sustained wind speed of TCs passing within 500 km and 250 km of Vanuatu, increased ~15 % 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 [14, 35]. Care must be exercised when interpreting the severity changes, especially prior to routine satellite observations that began in the 1970s, as data inhomogeneities can limit their usefulness for climate analysis [36, 37]. Nonetheless, globally, the increasing trend in the proportion of severe TCs (> Category 3 TCs) relative to the total number is also supported by Kossin et al. [38] (also see Tropical cyclone explainer and [39]).

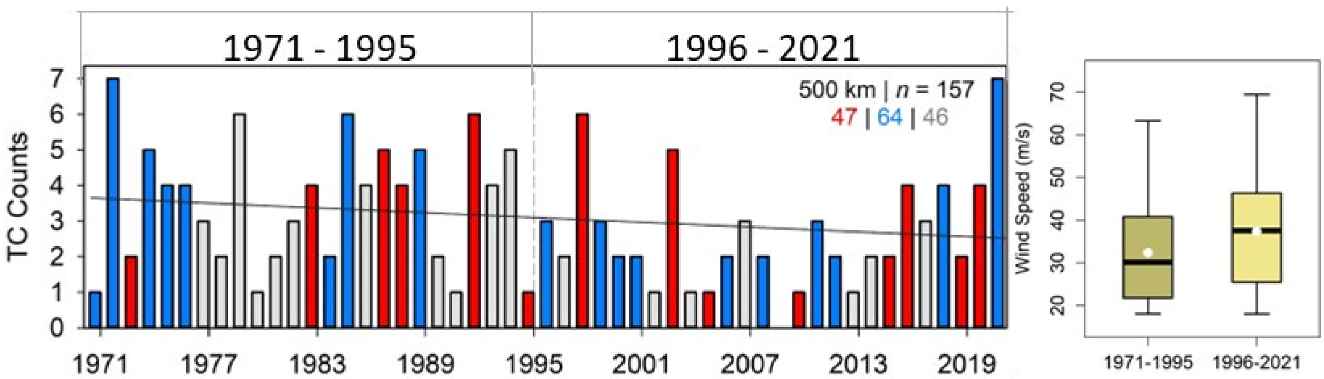

Figure 9 Observed number of cyclones categorised into El Niño (red), La Niña (blue) and neutral (grey), that have occurred within 500 km of Vanuatu during the 1971–2021 TC seasons. The total number of TCs is represented by n, which is also classified as El Niño (red font), La Niña (blue font), or neutral (grey font) ENSO conditions. A 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. The right panel shows the wind speed (m/s) distributions as boxplots for the two periods. 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.

Vanuatu is more susceptible to TCs during La Niña years than El Niño years (Figure 9). For instance, between the 1971 and 2021 seasons, TCs within 500 km of Vanuatu have been more frequent during La Niña years (~13 cyclones per decade) than El Niño and ENSO neutral years (~9 cyclones per decade). This result of more TCs occurring near Vanuatu during La Niña years is robust for different sizes of regional analysis areas, e.g. 500, 250 or 50 km [28] (see Tropical cyclone explainer).

Sea surface temperature

There is a trend of warming SST observed in the tropical Pacific, including around Vanuatu (Figure 5). In particular, recent cool seasons have been much warmer than the historical average. The regional SST has not cooled to below 25 °C since the 1997 El Niño event, while during the 1980s and 1990s such a low temperature threshold was reached five times. The increase in SST has been associated with an increase in marine heatwaves. The average annual duration of Pacific marine heatwaves was 5–16 days in the 1980s to 2000s but increased to 8–20 or more days during the 2010s [40]. The changing SST is posing challenges for temperature sensitive marine ecosystems including coral reefs, seagrass beds, and fish (see Marine heatwave explainer and, Coral reef, Seagrass and Sea turtle infobyte).

Sea level

One of the most pressing climate change concerns is the rise in global sea levels resulting from ongoing greenhouse gas emissions and the associated warming effect. In the western Pacific, including around Vanuatu, sea levels have risen faster than in the central and eastern parts of the tropical Pacific [41] (Figure 10). The sea level rise observed over the western tropical Pacific is about 10–15 cm for the 1993–2020 period [32], which is having adverse consequences for Vanuatu, particularly in low-lying coastal areas that are most vulnerable to flooding and erosion. It is noted vertical land motion due to earthquakes has offset some of the effect of global sea level rise on relative sea level in some locations (e.g. Port Vila) [42] (Figure 5). Furthermore, in Figure 10, the circles with dots indicate tide gauge trends that are less than interannual variability, with Port Vila tide gauge indicated with an arrow. However, Vanuatu remains vulnerable to the long-term effects of sea level rise.

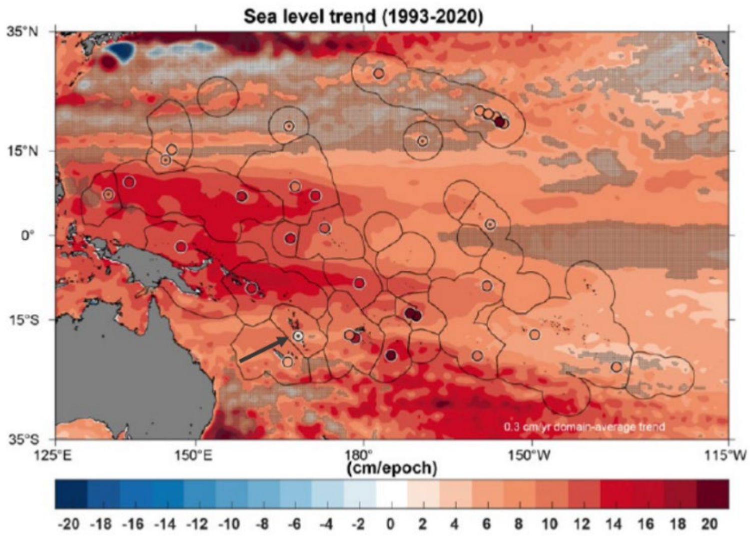

Figure 10 SSH trends (cm/epoch) from satellite altimetry (shaded contours) and sea level trends from tide gauges (circles) during 1993–2020. Trends that are less than interannual variability, which is determined by the standard deviation of monthly anomalies, are indicated by hatching and circles with dots for the altimetry and tide gauges, respectively. An arrow points to Port Vila in Vanuatu. Source: PCCM [32].

Figure 11 shows the annual counts of high sea level events for all of the tropical Pacific islands with long-term tide gauge measurements[2] and the increasing frequency of high sea level events, respectively, with most high sea level events recorded during the past five years.

The relatively few minor flooding days experienced in Port Vila since 2008 is in stark contrast to the increased occurrence of high sea levels recorded by most tide gauges in other tropical Pacific Islands. The tide gauge in Pago Pago, American Samoa, has recently (since 2010) been recording the most frequent number of extremely high sea levels, which is associated with land subsidence [43]. Note that the satellite-measured SSH trends for Pago Pago and Port Vila are similar (about 6 cm of sea level rise since 1993; Figure 10). Differing vertical land motions explain the differences in the relative sea levels recorded by the tide gauges in these locations [42, 43].

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

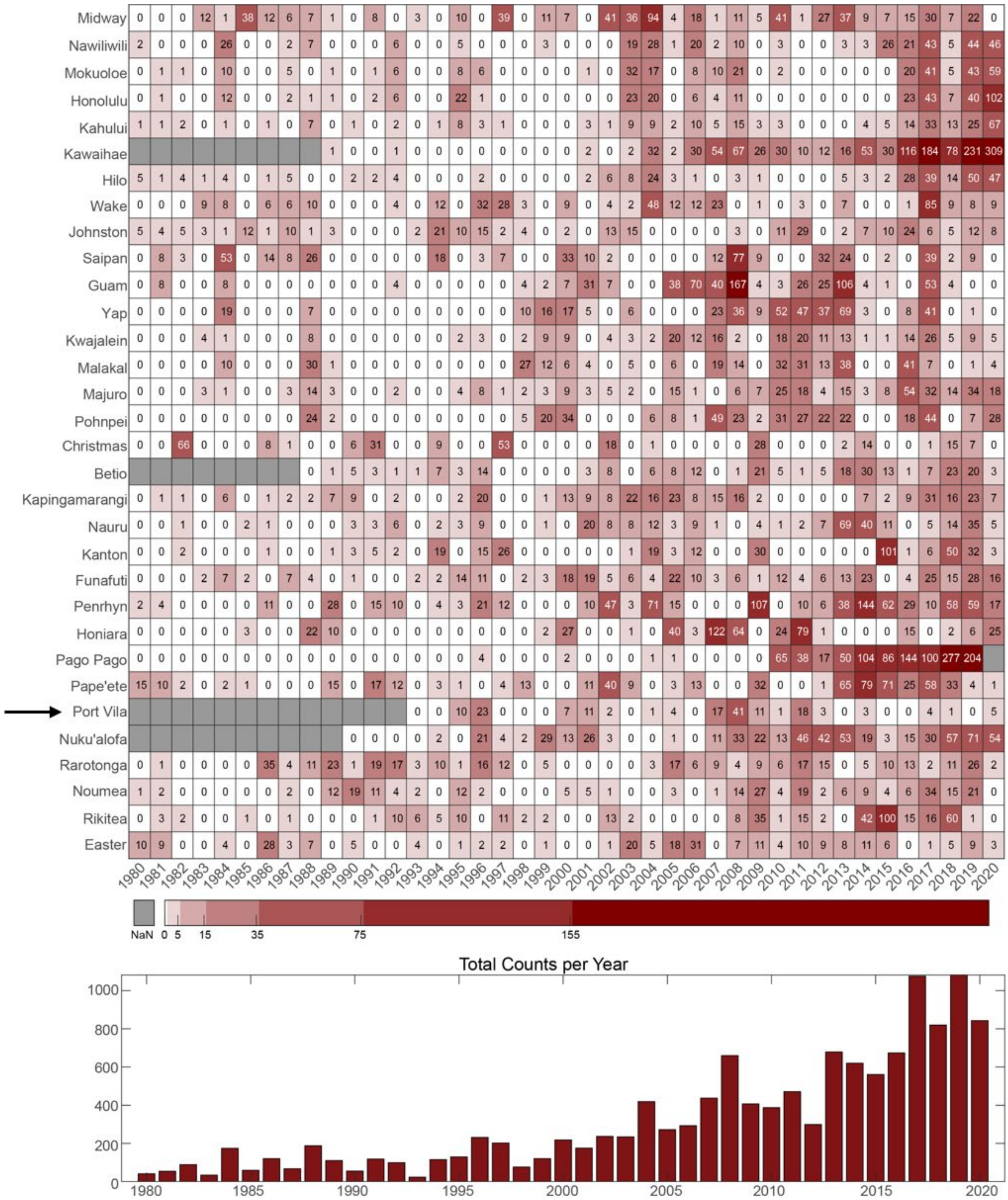

Figure 11 Minor flood frequency recorded at tide gauges in the tropical Pacific. The top plot shows the total number of minor flood days per year for 1980–2020. An arrow points to Port Vila in Vanuatu. The bottom plot shows the annual total number of minor flooding days for all stations combined. Adapted from PCCM [32] to include Port Vila.

Projected climate changes

Increasing concentrations of greenhouse gases and other human influences on the climate will lead to further climate change for Vanuatu. Many changes already being observed are projected to become larger, in direct relation to the amount of additional global warming that occurs. Likely changes include increases in the frequency and intensity of extremes such as marine heatwaves, heavy rainfall, droughts, and flooding associated with sea level rise [44, 45]. TC frequency is likely to decrease, however a greater proportion of severe TCs is expected [10, 28, 46]. In this section, we discuss the processes affecting these climate changes as well as their likely magnitudes.

Warming ocean and changing atmosphere

The future temperature change for Vanuatu will depend mostly on the amount of global greenhouse gas emissions and the corresponding amount of global warming [47] (see Greenhouse gas emissions factsheet). A recent study using the CMIP6 climate model experiments assessed future changes of SST, rainfall, and SSH in the tropical Pacific [9]. Projections relative to recent historical conditions were assessed for either 1.5 °C or 3.0 °C increases of Global Mean Surface Temperature (GMST) above pre-industrial levels, e.g. for seasonal SST at 3.0 °C GMST (Figure 12).

Similar to most oceanic tropical regions, the amount of warming for the Vanuatu region (including over surrounding ocean) is projected to be less than the global average [48, 49], however the change over land alone is likely to be similar to the global average. If the GMST warms by 3.0 °C, then the change in the tropical Pacific (and around Vanuatu) is likely to be about 2.3 °C (Figure 12) [9]. The local difference is somewhat smaller for lower emissions and lower global warming (1.5 °C versus 1.2 °C). Lower warming compared to some other regions does not directly mean lower impacts, as impact also depends on changes to other phenomena such as extremes as well as the exposure and vulnerability to climate risks. For Vanuatu and other island communities, the warming climate will continue to impact the economy, society and environment.

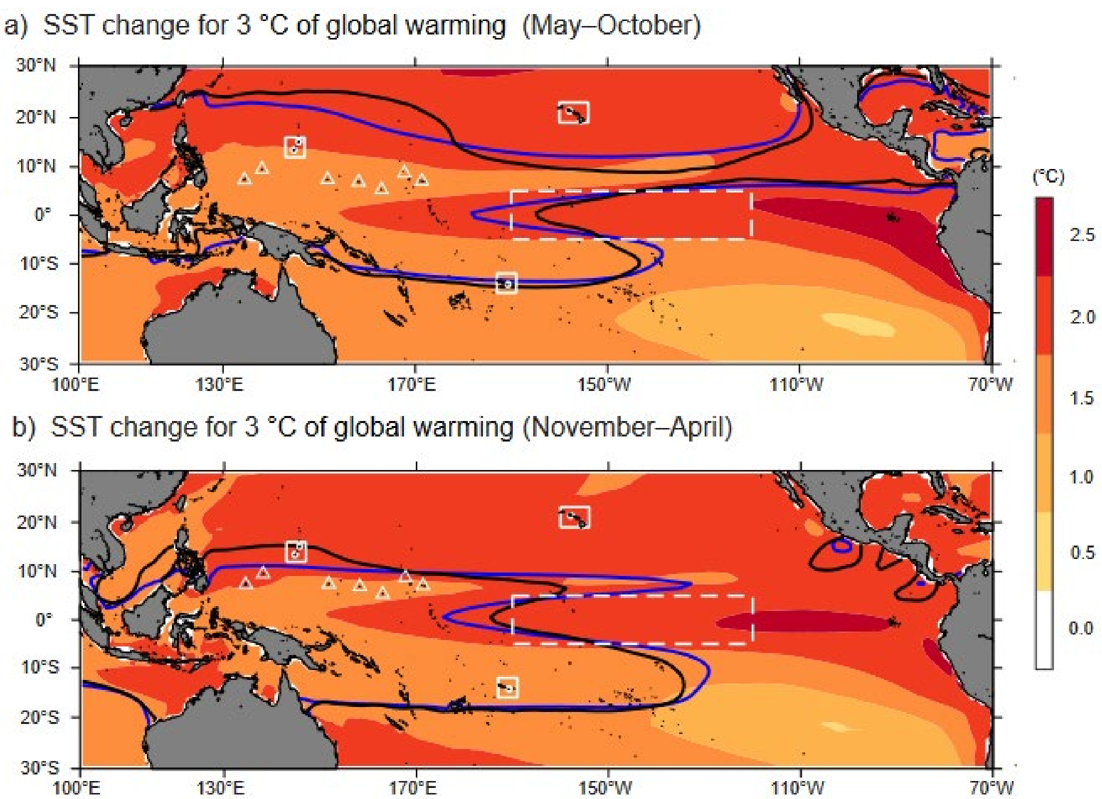

Figure 12 Multi-model mean SST changes with respect to 1985–2014 historical conditions for 3 °C of global warming (°C, colour bar). Two seasons are shown: (a), May–October; (b), November–April. Contour lines depict the 28 °C isotherm for the observed (black) and model-simulated historical (blue) conditions. More than 66 % of models agree on the direction of future change everywhere (no stippling).

Changing rainfall, droughts and storminess, including TCs

In response to this future warming, the tropical Pacific climate is projected to become wetter overall and also stormier at times, which is partly because of the ability of warmer air to contain more moisture [33, 50], however there are regional differences, and Vanuatu is in a region that may become wetter or drier. Here, we define storminess as including everything from heavy downpours to the most severe TCs. In the equatorial Pacific, which is expected to warm the most this century [48, 51], the projected increase in rainfall is also the greatest (Figure 15). In the central and eastern equatorial Pacific, all the CMIP6 climate models agree on a wetter future climate, whereas there is more uncertainty around many of the islands in the western tropical Pacific, particularly off the equator in the SPCZ and ITCZ regions, including Vanuatu [9]. Some islands in the western tropical Pacific may experience an overall drying trend [2, 52, 53].

Figure 13 shows that the CMIP6 rainfall projection is for uncertain future changes around Vanuatu (stippling). This uncertainty is because different climate models are indicating opposing atmospheric responses to greenhouse warming [53]. On the one hand, all the models simulate a mechanism of wet places tending to become wetter, because moisture will be more abundant in a warmer atmosphere. This "wet gets wetter" mechanism, if considered independently, suggests that rainfall around Vanuatu would increase. However, this mechanism is offset by an opposing mechanism that causes drying in the off-equatorial regions. The latter mechanism is especially strong in climate models that simulate a lot of subsiding air away from the places where future rainfall and atmospheric convection increase the most (i.e. near the equator), which is also the region projected to warm the fastest. If the "warmest gets wetter" mechanism dominates the future climate, then off-equatorial regions, like Vanuatu, will experience a drying trend. The future climate of Vanuatu is determined by possible future changes in the SPCZ, from a northern movement (Vanuatu becomes drier) or a southern movement (Vanuatu becomes wetter) [67].

How these climate change mechanisms balance in the coming decades will determine the future rainfall amounts for tropical Pacific islands, including Vanuatu. Figure 13 indicates that the climate models are split between wetter and drier rainfall projections for much of the south-western tropical Pacific. For Vanuatu, projected changes in annual average rainfall by 2050 are uncertain, i.e.-6 to +9 % for a low emissions pathway and –12 to +14 % for a high emissions pathway [31]. A simple way to consider the future change is in two contrasting 'storylines' of change in the SPCZ [67], where both should be considered plausible. This uncertainty in the future rainfall projections is an important consideration for policymakers and planners in Vanuatu who are faced with preparing for widely varying potential changes to the local hydrology and water resources.

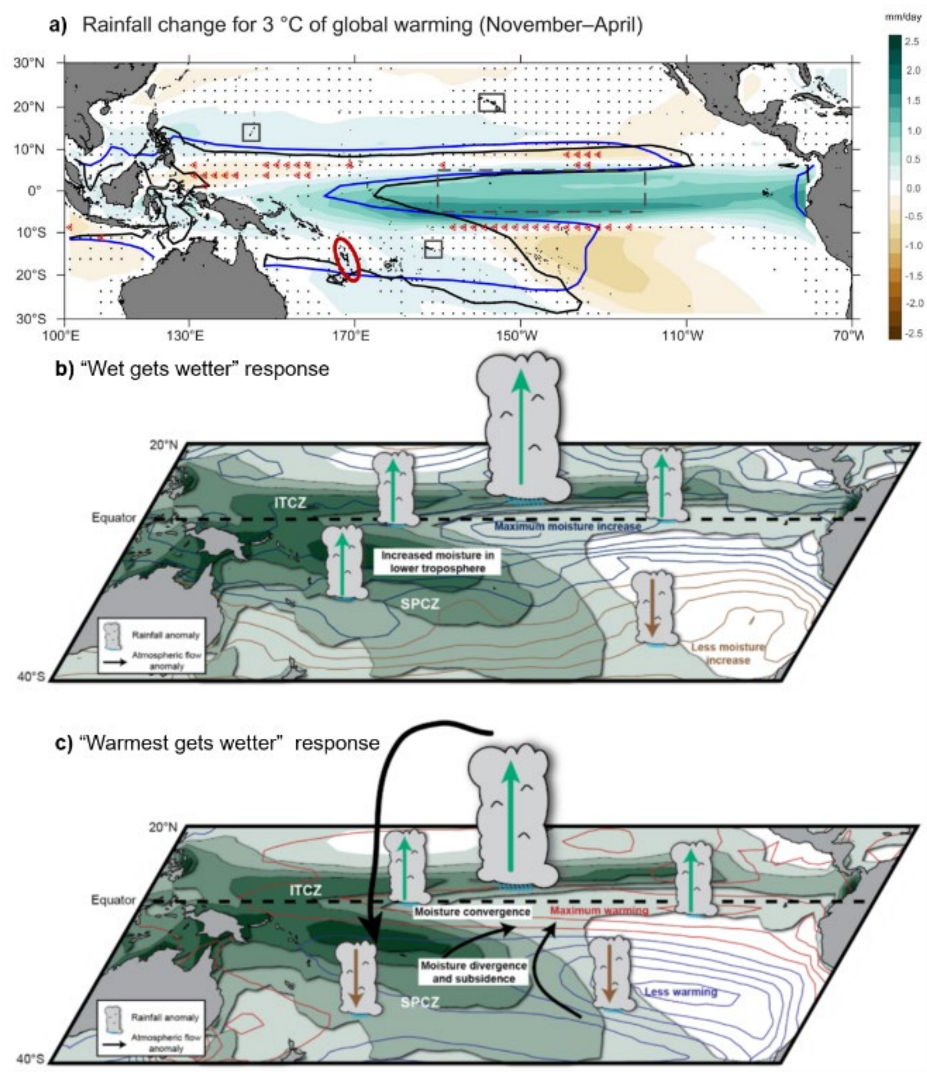

Figure 13 Future rainfall changes for Vanuatu are uncertain because of opposing atmospheric responses to greenhouse warming. a) Projected rainfall change for 3 °C of future warming according to CMIP6 experiments [9]. b and c) Schematics describing the "wet gets wetter" and "warmest gets wetter" responses to greenhouse warming [53].

Storms will continue to be a hazard for Vanuatu, regardless of any changes to average rainfall. TCs will continue to generate impacts including strong winds, heavy rain, and storm surges. And while the frequency of TCs is projected to decrease in most places, due to greenhouse warming increasing atmospheric stability [54], the intensity of the strongest TCs is expected to increase because of the increased available potential energy in a warmer ocean [55, 56].

Most of Vanuatu's extreme rainfall events are associated with weather systems other than TCs [12], such as thunderstorms, which must be considered in the context of future changes. Climate models are projecting a general increase in the intensity of extreme rainfall [57]. For extreme daily rainfall with return periods of 10–100 years, climate simulations for Port Vila showed an increase of about 21 % for 2040–2070 (medium emission pathway: RCP4.5), 30 % for 2070–2100 (RCP4.5), 40 % for 2040–2070 (high emissions pathway: RCP8.5), and 70 % for 2070–2100 (RCP8.5) [58]. In the climate models that were assessed, the greatest increases in extreme daily rainfall are in the projections with the largest increases in greenhouse gases (i.e. the RCP8.5 scenario in the CMIP5 experiment). A trend toward increasing extreme daily rainfall is consistent with a warmer atmosphere holding more moisture [50], because moisture abundance is an ingredient for intense storms.

Vanuatu is likely to continue experiencing occasional droughts, especially during future El Niño events. Considering that the multi-model mean projection is for little change in annual average rainfall (see Figure 13), it is likely that any future change in drought characteristics will be driven by warming temperatures (i.e. enhanced evapotranspiration) and greater climate variability (i.e. more extreme El Niño events [21] and the associated dry conditions in the western tropical Pacific). Some climate models suggest that extreme droughts may become more frequent for Vanuatu, especially for the highest emissions scenarios [57] (see Drought explainer).

Sea level rise

Sea levels are rising due to climate change, and this is a major threat to Pacific nations. Depending on the combination of global sea level rise and the specifics of local vertical land motion, as well as the distribution of sandy beaches, rocky cliffs and coral reefs, coastal communities and infrastructure in Vanuatu could be impacted in a variety of ways. For instance, rising sea levels relative to land will lead to more frequent and intense coastal flooding and erosion in many places, which in turn increases the risk of damage to property and infrastructure [30]. If instead there are periods when the rate of uplifting land cancels some of the sea level rise, then there will be some mitigation of the coastal flooding risk, at least temporarily (i.e. perhaps for a decade or two). In addition, natural climate variability, such as that associated with ENSO, impacts regional sea level variability and extremes on shorter (seasonal-to-interannual) time scales [26, 59].

Climate modelling research suggests that greenhouse warming may enhance El Niño related sea level extremes, particularly in the south-western tropical Pacific, where very low sea level events are projected to double in occurrence [27]. High sea level events during La Niña are also projected to become more extreme, potentially leading to extreme months or seasons with many days of high-tide flooding clustering together [60]. This could result in critical frequencies of flooding occurring sooner than expected due to global sea level rise alone. However, all climate models project more "El Niño" like conditions, but observations over recent decades demonstrate more "La Niña" like conditions, so climate models may be getting regional simulations wrong, particularly in the Pacific [68].

The rate of global sea level rise will ultimately have the largest effect on relative sea level change for Vanuatu. Sea level rise depends on the amount of greenhouse warming and is directly determined by both how much melting ice flows from the land to the ocean as well as how much the ocean warms and expands [61]. Considering that there are a multitude of uncertainties for all the components affecting sea level rise, it is not surprising that there is a large range in projections, especially by the end of the 21st century. For Vanuatu, projected changes in annual average sea level by 2050 range from 17–30 cm for a low emissions pathway to 22–37 cm for a high emissions pathway [31]. By 2100, the spread of sea level rise projections increases to between 33–64 cm for a low emissions pathway and 68–122 cm for a high emissions pathway [31]. Also, the IPCC 6th assessment found a 'low likelihood high impact' outcome where Antarctic ice cliffs and shelves more rapidly disintegrate, that would lead to much higher sea level rise [47]. Vertical land motion is also an important source of localised uncertainty for Vanuatu (see the trend differences between regional SSH and local sea level in Figure 11). Regardless of the remaining uncertainties about the amount of greenhouse warming and glacier melt, it is unequivocal that global sea level rise will continue this century [47]. It is also unlikely that uplifting land motions will be sufficient to completely offset future local sea level rise affecting Vanuatu's coastal areas.

As a result of sea level changes, it is likely that Vanuatu will face challenges in the coming decades, particularly in terms of coastal infrastructure and the sustainability of its economy and society. Addressing these challenges will require effective adaptation and mitigation strategies, including investments in coastal protection, water management, and disaster risk reduction.

Projected variability changes under future climate conditions

In the tropical Pacific, with 3.0 °C of GMST warming, the CMIP6 projections show increased interannual (year to year) variability of SST, rainfall, and SSH (Figure 14). The increased variability is especially large and consistent across climate models in the Niño 3.4 region, which is the equatorial area most directly affected by ENSO.

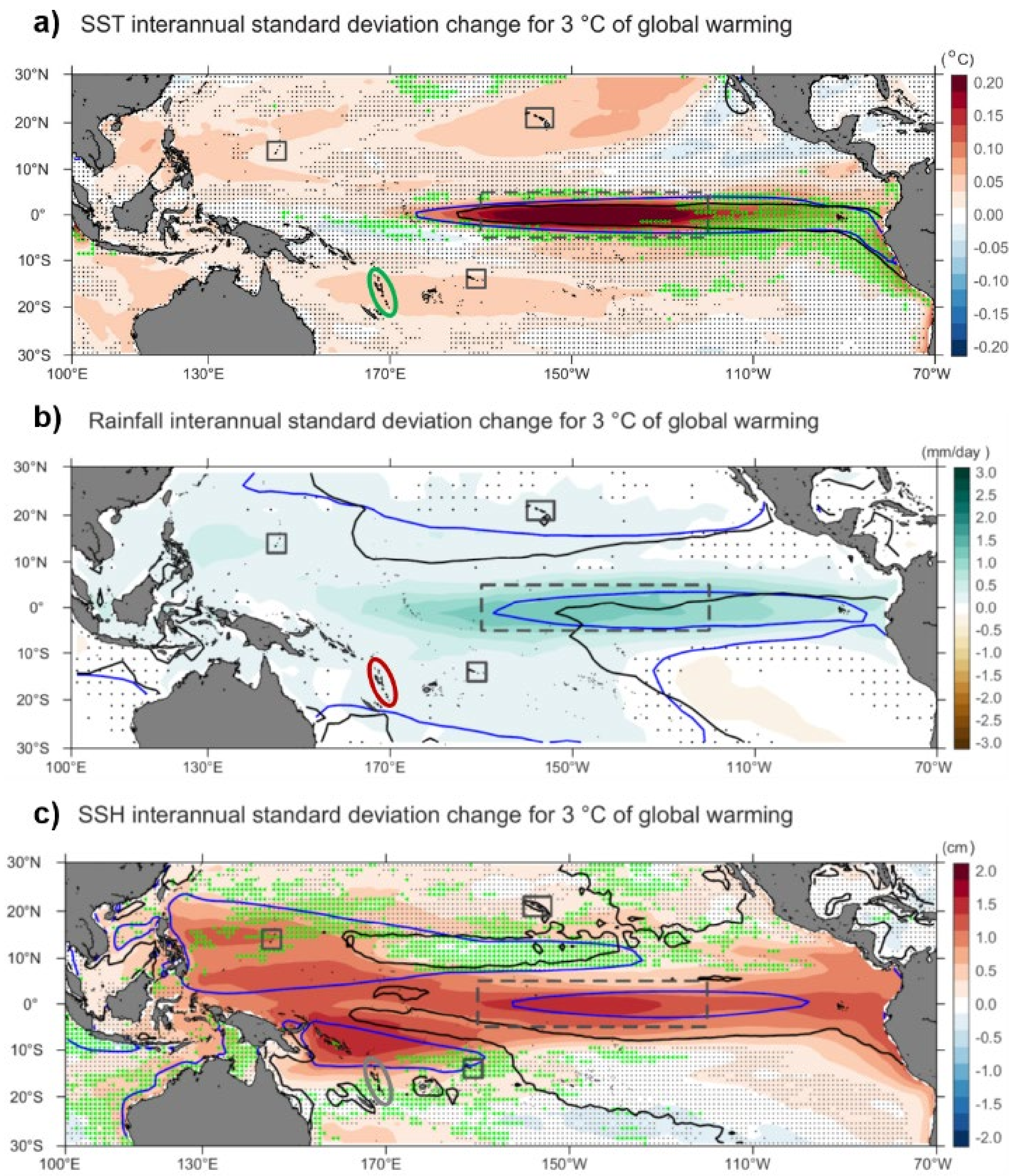

Figure 14 Projected change of SST (a), rainfall (b), and SSH (c) variability for 3 °C of global warming in CMIP6 climate model experiments. Black and green stippling indicates areas of more uncertainty or the most uncertainty, respectively. Vanuatu is circled and the Niño 3.4 region is boxed. Adapted from Dhage and Widlansky [9].

Increased variability of SST and rainfall may result in more frequent or intense marine heatwaves as well as the increasing severity and likelihood of both flooding and droughts. Climate models also indicate that future sea level variability, such as the interannual oscillations that alter local astronomical tidal cycles and contribute to coastal impacts [27, 62], will increase in many parts of the tropical Pacific. This is consistent with projected increases in extreme La Niña and El Niño events due to climate change [21, 24, 63]. Thus, the projected changes in ENSO extremes in the tropical Pacific could have significant impacts on Vanuatu's weather patterns and coastal communities.

While overall TC frequency is projected to decrease for the south-western tropical Pacific, including Vanuatu, more TCs are projected in the future during El Niño events compared with present climate El Niño events, although there is low-medium confidence in this projection [64, 68]. The opposite change during future La Niña events is also projected (i.e. fewer TCs compared to the present climate. The projection of overall fewer but stronger TCs has the potential to cause more destructive impacts on coastal communities and infrastructure [16, 28, 65].

Implications of climate variability and change for Vanuatu

Vanuatu is facing significant weather and climate changes in the coming decades that will have far-reaching impacts on the country's environment, economy, and society. These changes include sea level rise, warming of the ocean and atmosphere, as well as more extreme ENSO events associated with likely increasing variability of SST, rainfall, and sea level. Climate variability will be superimposed on long-term changes, leading to an increase in extreme events such as hot days, heavy rainfall, marine heatwaves, droughts, and sea level extremes. Fewer but stronger TCs are also projected. Coastal communities and vulnerable infrastructure are likely to be the most affected, with potentially negative impacts on buildings, transport, water resources, agriculture, livelihoods and natural ecosystems (see Van-KIRAP sectoral infobytes).

To address these challenges, effective adaptation and mitigation strategies will be crucial. Coastal protection, water management, and disaster risk reduction investments are essential to help reduce the negative impacts of climate change. Improved forecasts, early warning systems, and better flood monitoring can support emergency management efforts.

There remain many uncertainties about future climate variability and change, especially because there is a broad spread in possible greenhouse gas emissions pathways. Each pathway is based on plausible assumptions about future socio-economic development, energy use, land use, and air pollution. A low emissions pathway leads to 1.3–2.4 °C global warming by 2081–2100, relative to 1850–1900, while a high emissions pathway leads to 3.3–5.7 °C global warming by 2081–2100 [47]. Based on current international policies and pledges, the world is most likely heading for 2.2–3.4 °C global warming [66]. Much further emission reductions than those pledged are needed to meet the Paris Agreement target of keeping global warming below 2 °C (see Greenhouse gas emissions factsheet).

There is also uncertainty about the regional climate responses simulated by climate models for each emissions pathway. The CMIP5 climate model experiments have been replaced by the CMIP6 experiments using more advanced models and emissions scenarios. Even finer-resolution models are being used to 'downscale' the simulations over selected regions of interest, such as in the CORDEX and CORDEX-2 experiments (see Global climate models factsheet). Downscaling has been shown to improve the simulation of extreme weather events, especially in regions of complex topography like Vanuatu and many other Pacific Islands. However, downscaling methods have strengths and weaknesses, so uncertainties will remain about regional climate projections [47].

Nevertheless, this report provides a summary of the climate variability affecting Vanuatu now and in the future. It is essential to continue monitoring climate variability and change to improve our understanding of potential impacts on Vanuatu and other islands in the tropical Pacific. This information will be crucial in supporting adaptation and mitigation efforts, as well as for developing policies and programs that are appropriate to the unique challenges faced by these island communities. The National Sustainable Development Plan 2016–2030 provides a vision for development in Vanuatu. One of the five aspirations is enhanced resilience and adaptive capacity to climate change and natural disasters. Implementing this goal is critical to reduce the likelihood of harmful impacts associated with the observed and changing climate conditions discussed in this report.

References

1. Widlansky, M.J., P.J. Webster, and C.D. Hoyos, On the location and orientation of the South Pacific Convergence Zone. *Clim. Dyn.*, 2011. 36: p. 561–578 DOI: 10.1007/s00382-010-0871-6.
2. Brown, J.R., et al., South Pacific Convergence Zone dynamics, variability and impacts in a changing climate. *Nat. Rev. Earth Environ.,* 2020. 1: p. 530–543 DOI: 10.1038/s43017-020-0078-2.
3. Chand, S., et al., Climate processes and drivers in the Pacific and global warming: a review for informing Pacific planning agencies. *Climatic Change,* 2023. 176(5) DOI: 10.1007/s10584-022-03467-z.
4. Webster, P.J., The annual cycle and the predictability of the tropical coupled ocean–atmosphere system. *Meteor. Atmos. Phys.*, 1995. 56: p. 33–55.
5. Hoyos, C.D. and P.J. Webster, Evolution and modulation of tropical heating from the last glacial maximum through the twenty-first century. *Clim. Dyn.*, 2012. 38: p. 1501–1519 DOI: 10.1007/s00382-011-1181-3.
6. Johnson, N.C. and S.-P. Xie, Changes in the sea surface temperature threshold for tropical convection. *Nature Geoscience*, 2010. 3: p. 842-845 DOI: 10.1038/NGEO1008.
7. Johnson, N.C. and S.-P. Xie, Changes in the sea surface temperature threshold for tropical convection. *Nature Geoscience*, 2010. 3(12): p. 842-845.
8. Lindzen, R.S. and S. Nigam, On the role of sea surface temperature gradients in forcing low-level winds and convergence in the tropics. *Journal of Atmospheric Sciences,* 1987. 44(17): p. 2418-2436.
9. Dhage, L. and M.J. Widlansky, Assessment of 21st century changing sea surface temperature, rainfall, and sea surface height patterns in the tropical Pacific Islands using CMIP6 greenhouse warming projections. *Earth's Future,* 2022. (e2021EF002524) DOI: 10.1029/2021EF002524.
10. Kirono, D.G.C., et al., *National and sub-national climate projections for Vanuatu.* 2023, CSIRO: Melbourne, Australia.
11. Australian Bureau of Meteorology. *Pacific Climate Change Data Portal*. 2018. Available from: http://www.bom.gov.au/climate/pccsp/
12. Deo, A., et al., Tropical cyclone contribution to extreme rainfall over southwest Pacific Island nations. *Clim. Dyn.,* 2021. 56: p. 3967–3993 DOI: 10.1007/s00382-021-05680-5.
13. Vincent, E.M., et al., Interannual variability of the South Pacific Convergence Zone and implications for tropical cyclone genesis. *Climate Dyn.,* 2011. 36(9-10): p. 1881–1896 DOI: 10.1007/s00382-009-0716-3.
14. Government of Vanuatu, *Post-Disaster Needs Assessment Tropical Cyclone Pam*, March 2015. 2015. Government of Vanuatu: Port Vila, Vanuatu. Available from: https://www.dfat.gov.au/sites/default/files/post-disaster-needs-assessment-cyclone-pam.pdf
15. Knapp, K.R., et al., The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. *Bull. Amer. Meteor. Soc.*, 2010. 91: p. 363–376 DOI: 10.1175/2009BAMS2755.1.
16. Widlansky, M.J., et al., Tropical cyclone projections: Changing climate threats for Pacific Island defense installations. *Weather Clim. Soc.,* 2019. 11(1): p. 3–15 DOI: 10.1175/WCAS-D-17-0112.1.
17. Kessler, W.S. and S. Cravatte, Mean circulation of the Coral Sea. 2013. 118(12): p. 6385-6410 DOI: 10.1002/2013JC009117
18. Ganachaud, A., et al., The Southwest Pacific Ocean circulation and climate experiment (SPICE). *J. Geophys. Res. Ocn.*, 2014. 119 DOI: 10.1002/2013JC009678.
19. Holbrook, N.J., et al., *ENSO-driven ocean extremes and their ecosystem impacts Ch 18 in El Niño Southern Oscillation in a Changing Climate,* M.J. McPhaden, A. Santoso, and W. Cai, Editors. 2020, Wiley.
20. Matthews, A.J. and G.N. Kiladis, Tropical-extratropical interaction between high-frequency transients and the Madden-Julian oscillation. *Mon. Wea. Rev.,* 1999. 127: p. 661-677.
21. Cai, W., et al., ENSO and greenhouse warming. *Nature Clim. Change,* 2015. 5: p. 849–859 DOI: 10.1038/NCLIMATE2743.
22. McGregor, S., N.J. Holbrook, and S.B. Power, Interdecadal sea surface temperature variability in the equatorial Pacific Ocean. Part I: The role of off-equatorial wind stresses and oceanic Rossby waves. *J. Clim.,* 2007. 20: p. 2643–2658.
23. Trenberth, K.E., The definition of El Niño. *Bull. Amer. Meteor. Soc.,* 1997. 78: p. 2771–2777.
24. Cai, W., et al., Increased frequency of extreme La Niña events under greenhouse warming. *Nature Clim. Change.,* 2015. 5: p. 132–137.
25. Thompson, P.R., M.J. Widlansky, and Coauthors, Sea level variability and change [in "State of the Climate in 2021, Global Oceans"]. *Bull. Amer. Meteor. Soc.*, 2022. 103: p. S168–S172 DOI: 10.1175/BAMS-D-22-0072.1.
26. Widlansky, M.J., et al., An interhemispheric tropical sea level seesaw due to El Niño Taimasa. *J. Clim.,* 2014. 27: p. 1070–1081 DOI: 10.1175/JCLI-D-13-00276.1.
27. Widlansky, M.J., A. Timmermann, and W. Cai, Future extreme sea level seesaws in the tropical Pacific. *Sci. Adv.,* 2015. 1(8): p. e1500560 DOI: 10.1126/sciadv.1500560.
28. Sharma, K., et al., Impact of climate change on tropical cyclones over Vanuatu: A case for informing disaster planning and adaptation strategies. *Natural Hazards,* 2023 submitted.
29. Hague, B.S., B.F. Murphy, D.A. Jones, A.J. Taylor, Developing impact-based thresholds for coastal inundation from tide gauge observations. *Journal of Southern Hemisphere Earth Systems Science,* 2019. DOI: 10.1071/ES19024.
30. Ritman, M., et al., Past and future coastal flooding in Pacific Small-Island Nations: insights from the Pacific Sea Level and Geodetic Monitoring (PSLGM) Project tide gauges. *J. South. Hemisph. Earth Syst. Sci.*, 2022. 72(3): p. 202–217 DOI: 10.1071/ES22023.
31. CSIRO and SPREP, *'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for Vanuatu.* 2021. CSIRO: Melbourne, Australia.
32. Marra, J.J., et al., eds. *Pacific Islands Climate Change Monitor: 2021.* 2022. The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC). Available from: https://www.pacificmet.net/pacific-climate-change-monitor-report
33. Held, I.M. and B.J. Soden, Robust response of the hydrological cycle to global warming. *J. Climate,* 2006. 19: p. 5686-5699.
34. Iese, V., et al., Historical and future drought impacts in the Pacific islands and atolls. *Climatic Change,* 2021. 166(1): p. 1-24.

35. Government of Vanuatu, *Vanuatu Recovery Strategy 2020-2023: TC Harold and COVID-19.* 2020. Government of Vanuatu: Port Vila, Vanuatu. Available from: https://www.preventionweb.net/publication/vanuatu-recovery-strategy-2020-2023-tc-harold-covid-19

36. Chand, S.S., et al., Review of tropical cyclones in the Australian region: climatology, variability, predictability, and trends. *Climate Change,* 2019. 10(5): p. e602.

37. Klotzbach, P.J., et al., Trends in global tropical cyclone activity: 1990–2021. *Geophysical Research Letters,* 2022. 49(6): p. e2021GL095774.

38. Kossin, J.P., et al., Global increase in major tropical cyclone exceedance probability over the past four decades. *Proceedings of the National Academy of Sciences,* 2020. 117(22): p. 11975-11980.

39. Australian Bureau of Meteorology. *"What is a Tropical Cyclone?"* 2023. Available from: http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/understanding/tc-info/

40. Holbrook, N.J., et al., Impacts of marine heatwaves on tropical western and central Pacific Island nations and their communities. *Global Planetary Change,* 2022. 208: p. 103680.

41. Fasullo, J.T. and S.R. Nerem, Altimeter-era emergence of the patterns of forced sea-level rise in climate models and implications for the future. *Proc. Natl. Acad. Sci.,* 2018. 115(51): p. 12944-12949 DOI: 10.1073/pnas.1813233115.

42. Brown, N.J., et al., Vertical motion of Pacific Island tide gauges: combined analysis from GNSS and levelling. *Geoscience Australia,* 2020. DOI: 10.11636/Record.2020.003.

43. Han, S.-C., et al., Sea Level Rise in the Samoan Islands Escalated by Viscoelastic Relaxation After the 2009 Samoa-Tonga Earthquake. *J. Geophys. Res. Solid Earth,* 2019. 124(4): p. 4142-4156 DOI: 10.1029/2018JB017110.

44. Oppenheimer, M. and B. Glavovic, *Chapter 4: Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities Ch 4 in The Ocean and Cryosphere in a Changing Climate,* A. Abe-Ouchi, K. Gupta, and J. Pereira, Editors. 2019, IPCC. p. 169.

45. Lee, H., et al., *Synthesis Report of the IPCC Sixth Assessment Report (AR6).* 2023. Available from: https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf

46. Knutson, T., et al., Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society,* 2020. 101(3): p. E303-E322.

47. IPCC, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* 2021. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

48. Xie, S.-P., et al., Global warming pattern formation: Sea surface temperature and rainfall. *J. Climate,* 2010. 23(4): p. 966-986 DOI: 10.1175/2009jcli3329.1.

49. Wang, G., et al., Robust warming pattern of global subtropical oceans and its mechanism. *J. Clim.,* 2015. 28: p. 8574–8584 DOI: 10.1175/JCLI-D-14-00809.1.

50. Seager, R., N. Naik, and G.A. Vecchi, Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle in response to global warming. *J. Climate,* 2010. 23(17): p. 4651-4668 DOI: 10.1175/2010jcli3655.1.

51. Ma, J., S.-P. Xie, and Y. Kosaka, Mechanisms for tropical tropospheric circulation change in response to global warming. *J. Climate,* 2012. 25(8): p. 2979–2994 DOI: 10.1175/JCLI-D-11-00048.1.

52. Brown, J.R., A.F. Moise, and F.P. Delange, Changes in the South Pacific Convergence Zone in IPCC AR4 future climate projections. *Climate Dyn.,* 2012. 39: p. 1-19 DOI: 10.1007/s00382-011-1192-0.

53. Widlansky, M.J., et al., Changes in South Pacific rainfall bands in a warming climate. *Nat. Clim. Change,* 2013. 3: p. 417–423 DOI: 10.1038/nclimate1726.

54. Knutson, T.R., et al., Tropical cyclones and climate change. *Nat. Geosci.,* 2010. p. 1–7 DOI: 10.1038/ngeo779.

55. Emanuel, K.A., Thermodynamic control of hurricane intensity. *Nature*, 1999. 401: p. 665–669.

56. Sobel, A.H., et al., Human influence on tropical cyclone intensity. *Science*, 2016. 3553(6296): p. 242–246 DOI: 10.1126/science.aaf6574.

57. Kirono, D.G.C., et al., *National and sub-national climate projections for Vanuatu.* 2023, CSIRO: Melbourne, Australia.

58. Chand, S. and Coauthors, *Technical Report: Van KIRAP Rainfall and Windspeed Projections.* 2023. Vanuatu Climate Futures portal.

59. Widlansky, M.J., et al., Multi-model ensemble sea level forecasts for tropical Pacific Islands. *J. Appl. Meteorol.,* 2017. 56(4): p. 849–862 DOI: JAMC-D-16-0284.1.

60. Thompson, P.R., et al., A statistical model for frequency of coastal flooding in Honolulu, Hawai`i during the 21st century. *J. Geophys. Res. Ocn.*, 2019. 124(4): p. 2787–2802 DOI: 10.1029/2018JC014741.

61. Nerem, R.S., et al., Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proc. Natl. Acad. Sci.* U.S.A., 2018. 115(9): p. 2022–2025 DOI: 10.1073/pnas.1717312115.

62. Widlansky, M.J., X. Long, and F. Schloesser, Increase in sea level variability with ocean warming associated with the nonlinear thermal expansion of seawater. *Communications Earth & Environment,* 2020. 1: p. 1–12 DOI: 10.1038/s43247-020-0008-8.

63. Cai, W., et al., Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Clim. Change,* 2014. 4: p. 111–116 DOI: 10.1038/NCLIMATE2100.

64. Chand, S.S., et al., Projected increase in El Niño-driven tropical cyclone frequency in the Pacific. *Nat. Clim. Change,* 2017. 7: p. 123–127 DOI: 10.1038/nclimate3181.

65. Deo, A., et al., Severe tropical cyclones over southwest Pacific Islands: economic impacts and implications for disaster risk management. *Climatic Change,* 2022. 172(3-4): p. 38.

66. Climate Analytics (2023). Climate Action Tracker. Available from: https://climateactiontracker.org

67. Narsey et al (2023). Storylines of South Pacific Convergence Zone Changes in a Warmer World. *Journal of Climate,* 35(20), 6549–6567.

68. Sobel et al (2023). Near-term tropical cyclone risk and coupled Earth system model biases. PNAS 120(33). DOI: 10.1073/pnas.2209631120.