# Tropical Cyclones and Climate Change:
## implications for the Western Tropical Pacific

March 2022

Australian Aid
CSIRO
SPREP
Secretariat of the Pacific Regional Environment Programme

CSIRO and SPREP (2022). Tropical Cyclones and Climate Change: implications for the Western Tropical Pacific. Technical report by CSIRO and SPREP to the Australia-Pacific Climate Partnership funded Pacific NextGen Projections project. Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Program (SPREP). Melbourne, Australia. https://doi.org/10.25919/pbtc-1y82

Acknowledgements

This report has been prepared for CSIRO as part of Australia Pacific Climate Partnership-funded Next Generation Climate Change Projections for the Western Tropical Pacific project.

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The authors acknowledge Kate Morioka, Karen Pearce (Bloom Communication) and Anil Deo (Federation University) for their contributions to the report.

Hamish Ramsay (CSIRO) kindly reviewed drafts of this report.

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# Contents

# Summary

Impacts from tropical cyclones (TCs) in a future climate are likely to worsen globally as a consequence of human-induced climate change, growing coastal population and increasing coastal infrastructure. However, the climatological link between local-scale TCs and climate change is not clear for the Pacific Island countries (PICs), and therefore potential impacts are not well understood. This report clarifies scientific connections between the climatology of TCs and climate change with emphasis on 14 PICs: Palau, Papua New Guinea, Solomon Islands, Vanuatu, Fiji, Tonga, Samoa, Niue, Cook Islands, Kiribati, Tuvalu, Marshall Islands, Nauru and the Federated States of Micronesia, as well as Timor-Leste.

Major findings presented in this report include:

- The El Niño Southern Oscillation (ENSO) is a major driver of year-to-year variability in TCs impacting PICs.
- Over the past decades, the mean number of TCs impacting PICs has declined. Over the same period, however, the number of severe TCs impacting the island nations has increased considerably.
- In a future climate, the mean number of TCs is projected to decrease further in the Pacific, with the exception of regions near Marshall Islands in the Central North Pacific where projections are for an increased TC activity.
- ENSO will continue to be a dominant large-scale climate process influencing the natural variability of TCs in future under greenhouse warming. However, 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 (and less frequent during future climate La Niña and neutral periods than their present-climate counterparts).
- Climate model experiments, supported by an understanding of theoretical mechanisms, point towards a likely increase in severe TCs and associated rainfall globally as climate warms. For the Pacific, TC-induced extreme wind gusts and rainfall are also likely to increase under warmer climate conditions.

Decision-making for future planning and development in PICs will need to take these changes into account for purposes of informing hazard-based impact and associated vulnerability and risk assessments. It is proposed that decision-making should also be in the context of standardised scenario analysis framed around NextGen climate projections to ensure appropriate consistency, scalability and scientific rigour in applications.

# 1 Overview

Tropical cyclones (TCs) are one of the costliest natural disasters impacting communities in Pacific Island countries (PICs) due to their high exposure and vulnerability; the latter in large part due to limitations on their adaptive capacity. Strong winds, coupled with heavy rainfall and storm surges, often have devastating consequences for life and property. The damage and mitigation costs associated with these events have increased in recent decades and will continue to increase due to growing coastal settlement and infrastructure development and increasing construction and replacement costs (Kumar and Taylor 2015). For example, severe TC *Pam* in 2015 caused a total economic loss of over US$449.4 million in Vanuatu (Esler 2016). This is equivalent to 64.1% of Vanuatu's gross domestic product. Similarly, severe TC *Winston* (February 2016) crippled Fiji's economy, causing devastating damages to infrastructure and social security. In January 2020, TC *Tino* inflicted widespread destruction across Tuvalu, destroying public infrastructure and several homes, as well as crops and island vegetation through coastal flooding and storm surges. Costs to the government are in the order of tens of millions of US dollars in recovery costs (Asian Development Bank 2020).

Historically, TC *Winston* in 2016 was the most intense cyclone on record, as well as the strongest to make landfall, in the Southern Hemisphere. TC *Pam* was the second most intense cyclone to have formed in the South Pacific and is considered as the worst natural disaster in the history of Vanuatu. Several other severe TCs have recently occurred in the Pacific within a relatively short span of time. For example, severe TC *Gita* (February 2018) was the strongest system on record to affect Tonga. In April 2020, TC *Harold* was the second-strongest cyclone to affect Vanuatu, after TC *Pam*. Similarly, TC *Yasa* (December 2020) was the strongest cyclone formed in the South Pacific after Winston. All these events have not only caused extensive destruction and human fatalities, but also rekindled a surge of questions around the debate "whether anthropogenic-induced climate change has made TCs more severe and, if so, how the frequency and intensity of these events are likely to change in future under greater warming?"

The answers to these questions are not simple, particularly for Pacific Island countries where substantial limitations in the availability and quality of observed TC records, compounded by strong natural variability, have created barriers to the scientific understanding around detection and attribution of TC trends. Likewise, the future climatology of TCs in the Pacific is technically challenging due to the dynamic nature of the underlying drivers of TCs and the physical limitations, and 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. Nonetheless, there is no doubt that human activities have significantly contributed to global climate change, particularly after the mid-twentieth century when the earth has warmed rapidly. Substantial evidence now exists that large-scale environmental conditions which support TC activity have changed significantly due to anthropogenic global warming (Knutson et al. 2019).

In this report, our main emphasis is to examine TC variability and trends for PICs, as well as to provide new information on future climate projections under global warming. We also discuss impacts of severe TC events and their implications for adaptation options in a changing climate. Note that most settlements in PICs are generally along the coastline (Andrew et al. 2019), with significant components of infrastructure located in the immediate vicinity of the shorelines (Kumar and Taylor 2015). This is particularly concerning as coastal shores are highly exposed to TC-induced impacts. For example, degraded reefs under intensified TCs, combined with the effects of increasing sea-level rise, can cause a substantial increase in the wave height and storm surges. Such changes can have significant repercussions on beach erosion, saltwater intrusion into groundwater and damage to infrastructure and food sources (Storlazzi et al. 2018; Duvat and Magnan 2019). Therefore, developing climate change adaptation and mitigation strategies are imperative, particularly for the highly vulnerable coastal communities where TC-induced impacts are concerning.

# 2 Tropical cyclone occurrence over Pacific Island countries

Most Pacific Island countries are small in size, have low elevations and are scattered across the tropics, exposing at least some of them directly to the impacts of TCs each year. Three prominent climatic features that affect convective activity such as TCs in the tropical Pacific are the South Pacific Convergence Zone (SPCZ), the Intertropical Convergence Zone (ITCZ) and the West Pacific Monsoon (WPM) (Fig. 1). The SPCZ spans the southwest Pacific Ocean, extending northwest-southeast diagonally from near the Solomon Islands (0°, 150°E) towards French Polynesia (30°S, 120°W). It is more active during the southern hemisphere summer months of November to April, and significantly affects the climate of countries like Cook Islands, Fiji, Nauru, Niue, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu. The ITCZ lies just north of the equator in the northwest Pacific Ocean during the northern hemisphere summer months (i.e., June-August), and influences the climate of the Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau and Papua New Guinea. Both the SPCZ and ITCZ merge with the WPM in the maritime continent region, which spans countries like Timor-Leste.

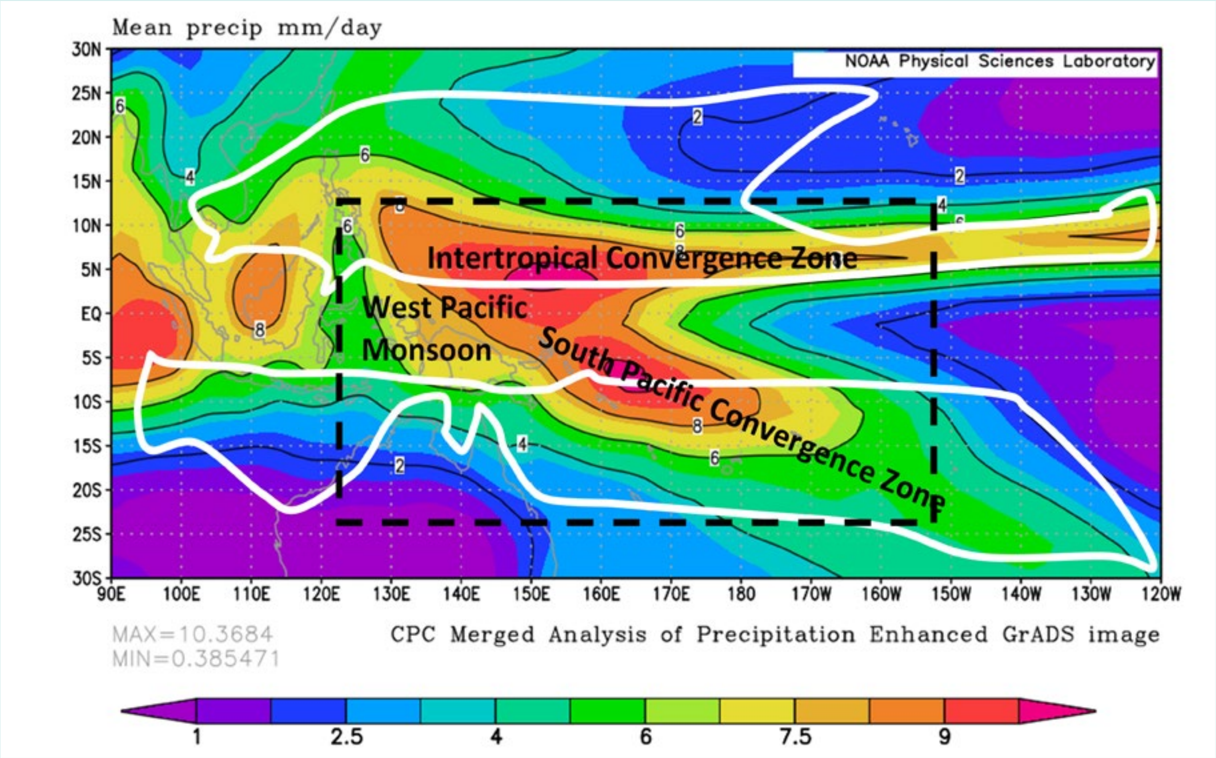


**Figure 1.** The average locations of the South Pacific Convergence Zone, the Intertropical Convergence Zone and the West Pacific Monsoon in the tropical Pacific region, defined using the mean daily precipitation over the period 1979-2020 (colour shadings and black contours). Mean TC formation regions (enclosed within white contours) for the summer-months (July-September, northwest Pacific, and January-March, southwest Pacific) are derived using the information from Tory et al. (2020). Dashed black box encloses Pacific Island nations.

TCs are frequently formed within the SPCZ, ITCZ and WPM regions during the northern and the southern hemisphere summer seasons when convective activity is high (Chand et al. 2020; Tory et al. 2020) (see regions within the white lines in Fig. 1). Climatologically, TCs formed in the SPCZ region often track in the southeast direction, whereas those that are formed in the ITCZ and WPM regions generally track in the northwest and southwest directions, respectively (Fig. 2). Consequently, island countries that lie along or poleward of the mean position of the SPCZ, ITCZ and WPM often experience relatively large number of TCs each year, as opposed to those that lie equatorward or farther east.

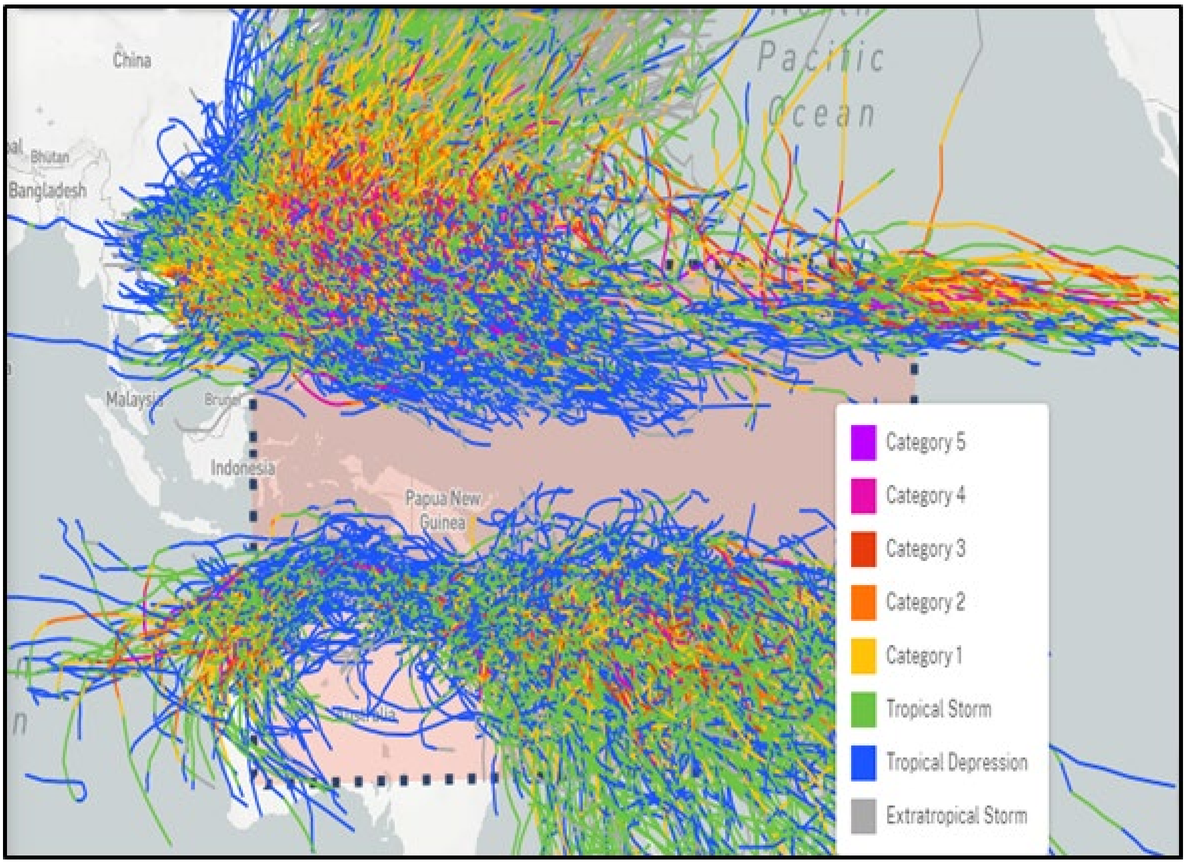


**Figure 2.** TC tracks that originated in the domain enclosing PICs and Timor-Leste (15°N-30S°; 120°E-150°W) over the period 1970-2018. Colour coding denotes TCs of different intensity categories based on the Saffir-Simpson scale where 1-minute sustained wind speeds are used for the classification: Tropical Depressions (< 62 km/hour), Tropical Storms (62-118 km/hour), Category 1 (119-153 km/hour), Category 2 (154-177 km/hour), Category 3 (178-208 km/hour), Category 4 (209-251 km/hour) and Category 5 (>251 km/hour). Note cyclones of Category 3 and higher are often referred to as "major hurricanes" or "severe cyclones" as in our case.

For example, the southwest Pacific Island countries such as Solomon Islands, Vanuatu, Fiji and Tonga often experience three or more TCs passing within the distance of 500 km each year (Fig. 3a). Of these, at least one TC can reach within the 50 km distance from these island nations (Fig. 3b). Note 500 km radius is chosen to demonstrate effects if far-located TCs, whereas 50 km indicates direct impacts. In the northwest Pacific Ocean basin, countries like Palau and the Republic of the Marshall Islands can experience at least three TCs per year passing within the 500 km distance, whereas for the Federated States of Micronesia, the annual number of TCs can exceed six. Island nations that are located equatorward and farther east – such as Tuvalu, Kiribati, Niue, Samoa and Cook Islands – often experience relatively fewer TCs than the other Pacific Island nations. However, TCs over these island nations can be modulated substantially on a year-to-year basis; we are not aware of any TC that has affected Nauru since the formal record has begun.

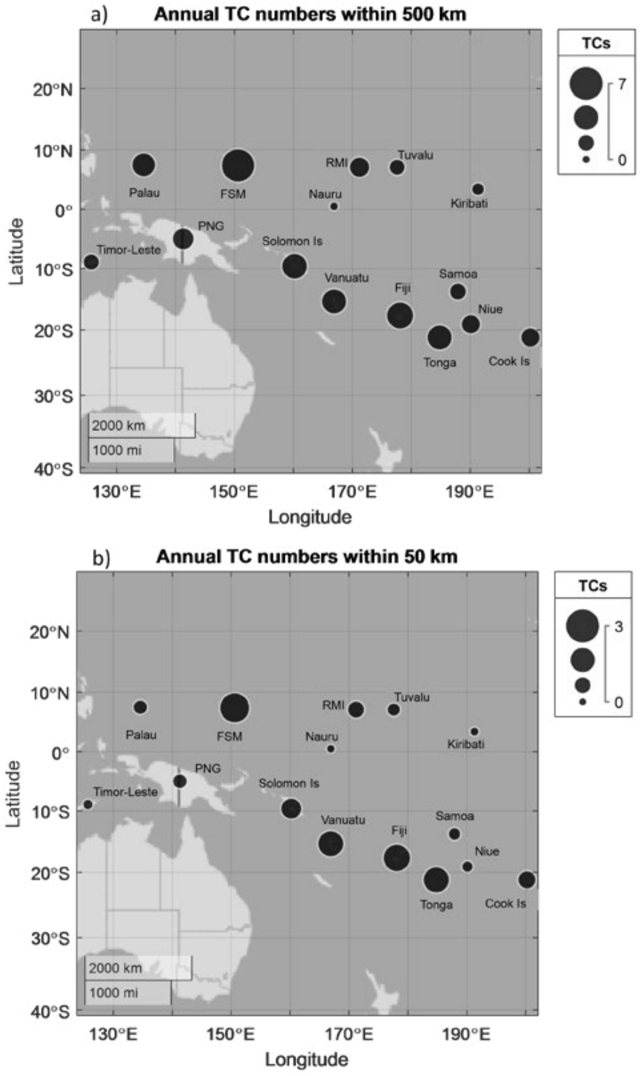


**Figure 3.** Mean number of TCs (i.e., with classification of tropical storms or higher, as per Figure 2) that passes within the (a) 500 km and (b) 50 km of the Pacific Island nations.

The major driver of the year-to-year variability of TCs in the Pacific is the El Niño Southern Oscillation (ENSO) phenomenon. Effects of ENSO on the Pacific TCs are well documented (Chand and Walsh 2009; Chand et al. 2020). In El Niño years, in the southwest Pacific, TC activity shifts north-eastward right across to the Cook Islands and French Polynesia with the greatest incidence around the dateline, extending east-southeast of the Fiji Islands. Simultaneously, low activity dominates the Coral Sea and Australian regions. In contrast, the reverse occurs during La Niña years when tropical activity is displaced south-westward into the New Caledonia, Coral Sea and Australian regions, with relatively low activity east of about 170° E. In the northwest Pacific Ocean basin, TC activity generally shifts southeast during El Niño and northwest during La Niña years (Lin et al. 2020).

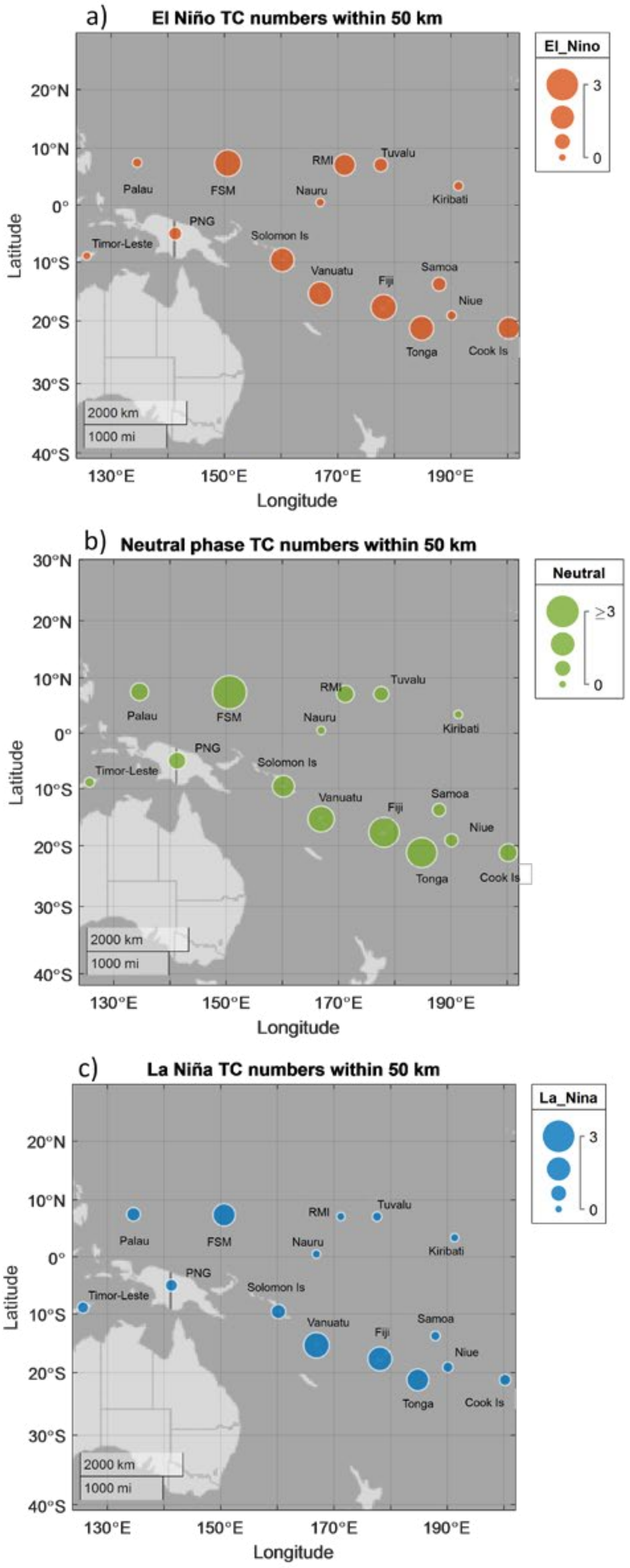


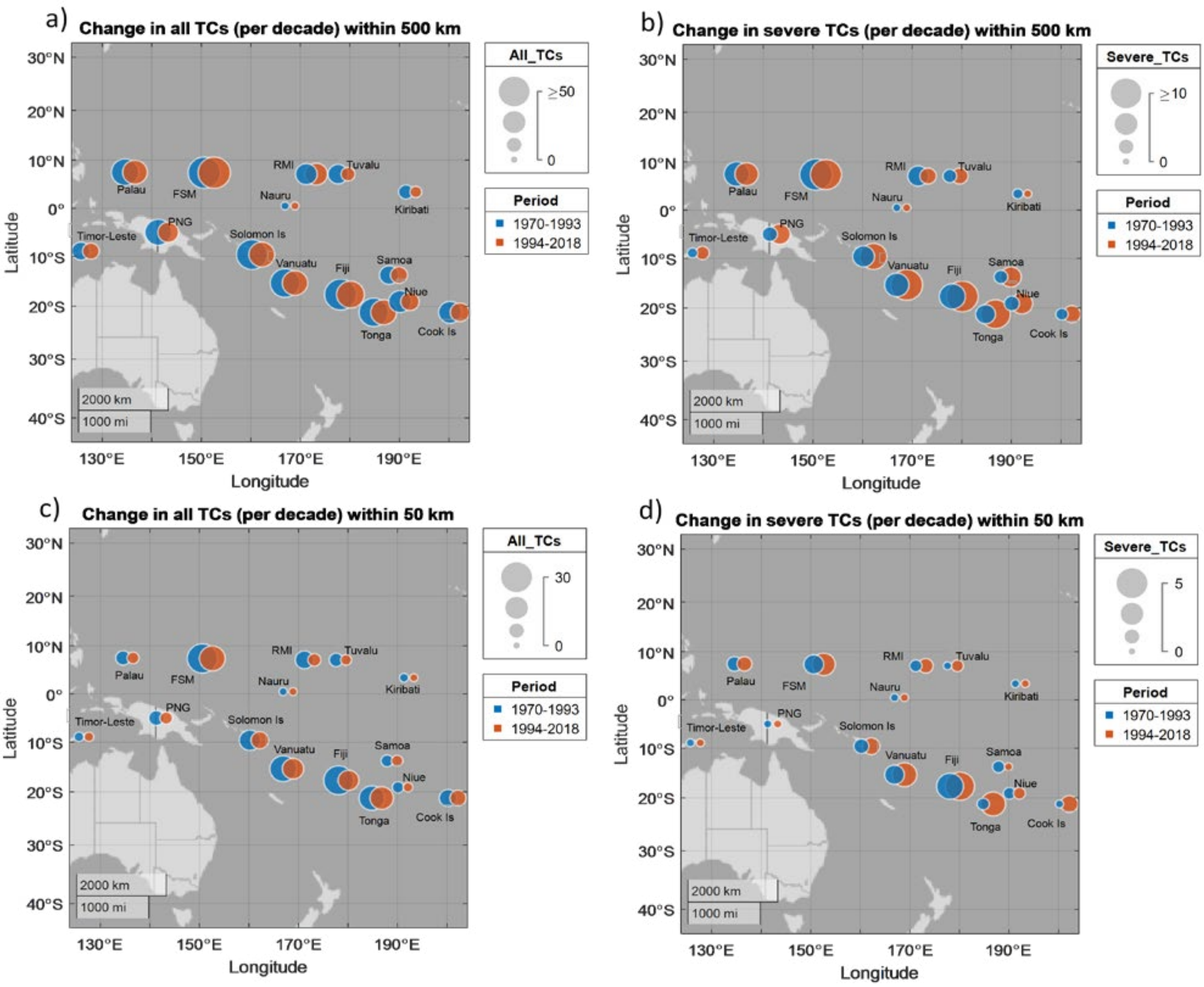
**Figure 4.** As per Figure 3b, but for TCs in different ENSO phases: (a) El Niño, (b) Neutral and (c) La Niña.

At island-scale, ENSO-related systematic shifts in annual TC numbers between the different phases of ENSO are very apparent in the Pacific (Fig. 4). In the northwest Pacific, TCs passing within 50 km of the Republic of the Marshall Islands and Tuvalu are particularly enhanced during El Niño compared with La Niña years. Similarly, in the southwest Pacific, substantially more TCs are likely to impact countries like Samoa and Cook Islands during El Niño than La Niña years. Interestingly, countries such as Vanuatu, Fiji and Tonga are always vulnerable to TC impacts, though it is likely that intensity of TCs impacting these island countries can be more severe during El Niño than La Niña years (Chand and Walsh 2009).

# 3 Observed tropical cyclone trends and climate change

Understanding likely changes in TC characteristics at the island-scale due to global warming can be difficult. This is partially because of the lack of long-term TC records in the Pacific for detection and attribution of climate change signals and partially because of the large deficiencies and biases in climate model simulations of regional and local-scale TCs (Knutson et al. 2019, 2020). Reliable observations of TCs became available only from around the 1970s when satellite monitoring became operational. Whether these few decades of data are sufficient to adequately resolve climate change signals, particularly in presence of large climate variability across and between decades, is still a challenging scientific problem.

Regardless, there is substantial evidence now that large-scale environmental conditions that support TCs are changing as a result of anthropogenic climate change (Walsh et al. 2015; Knutson et al. 2019). For example, changes in sea surface temperature (SST) are likely to drive regional and global-scale changes in deep convection, wind shear and middle troposphere moisture content (Sugi and Yoshimura 2012; Sugi et al. 2012; Chu et al. 2020). There is clear evidence that the total number of TCs affecting PICs have declined – but the frequency of severe TCs has increased considerably – between the two climatological periods over the past decades: 1970-1993 and 1994-2018 (Fig. 5). For most PICs, the decline in the total number of TCs passing within 500 km is up to 30% (Fig. 5a). The decline is even larger (i.e., up to 60% in some cases) for TCs reaching within 50 km of the island nations (Fig. 5c). In contrast, the number of severe TCs (i.e., category 3 and higher based on the Saffir-Simpson scale) reaching within 500 km (Fig. 5b) and 50 km (Fig. 5d) have increased substantially for the island nations, particularly those in the southwest Pacific. Note that even though the direction of change in frequency of severe TCs remains robust for most island countries using data from more recent periods (i.e., 1980-2000 and 2001-2018), care must be exercised when interpreting the results in the context of climate change due to dominant natural variability.



a) Change in all TCs (per decade) within 500 km

b) Change in severe TCs (per decade) within 500 km

c) Change in all TCs (per decade) within 50 km

d) Change in severe TCs (per decade) within 50 km

**Figure 5.** Changes in the mean number of TCs and severe TCs (per decade) between the two climatological periods: 1970-1993 and 1994-2018 passing within 500 km (a, b) and 50 km (c, d). Severe TCs are those that reached at least category 3 based on the Saffir-Simpson classification scale.

We note that over the past decades considerable warming of SST in the Pacific region has occurred. This has caused an increase in the mid-tropospheric saturation deficit and a reduction in the upward mass flux, as well as an increase in environmental vertical wind shear over the two climatological periods of 1970-1993 and 1994-2018. Changes in these factors (not shown) are believed to have created a less conducive environment for TC formation in the entire Pacific during the latter period, hence the decline in TC numbers. As for the increased severity of TCs impacting the island countries between the two periods under consideration, we note that the maximum potential intensity – a theoretical concept that evaluates the maximum intensity a TC can reach given the underlying thermodynamic environment such as SST and mid-tropospheric humidity – is considerably higher in the 1994-2018 period compared with the earlier period (Fig. 6). Increasing potential intensity conditions favour intensification of TCs as noted for PICs (e.g., Bister and Emanuel 2002).

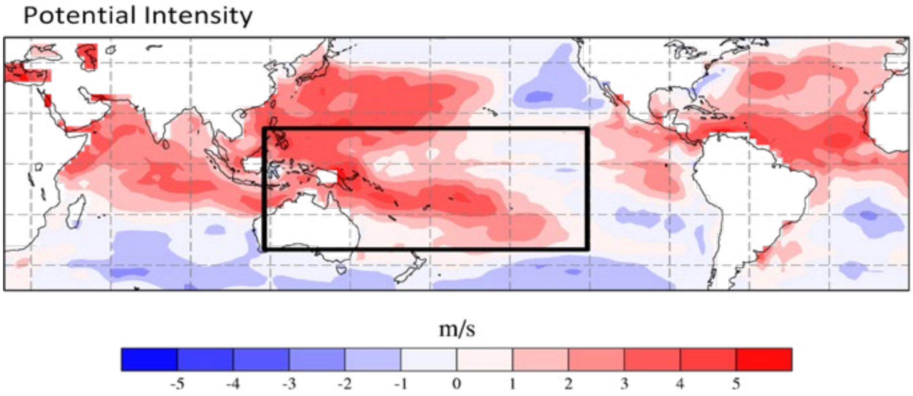


**Figure 6.** Map showing difference in the potential intensity between the periods 1994–2018 and 1970–1993 (box encloses the Pacific region). The figure is obtained from Deo et al. (2021).

We also find that due to the increasing potential intensity conditions, TC-induced (and even non-TC induced) extreme rainfall activity over PICs have increased considerably during 1994-2018 compared with 1970-1993 period (Fig. 7). However, it is important to note that while there are indications of observed changes in the TC and non-TC induced extreme rainfall patterns, large natural variability is also apparent. Further investigations are required to properly attribute any observed changes in TC rainfall to anthropogenic global warming as more observation records become available in future.

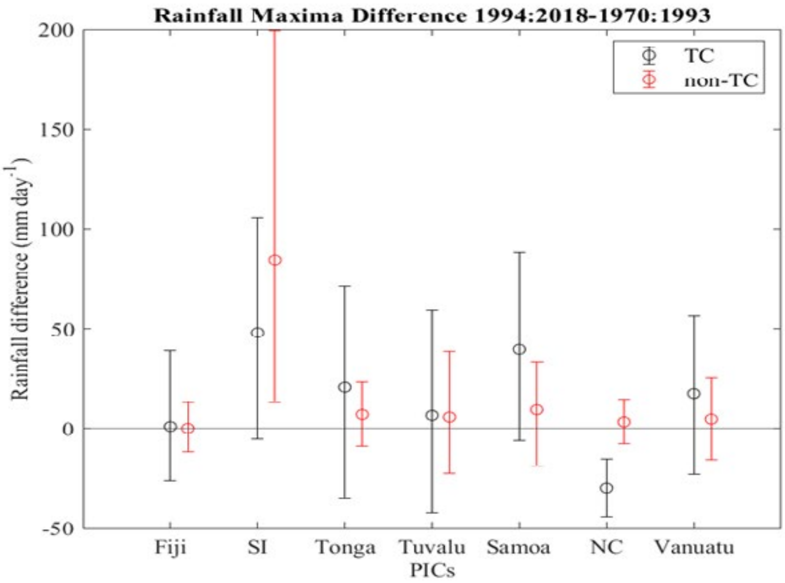


**Figure 7.** Difference in mean annual maxima daily rainfall associated with TCs and non-TCs for South Pacific Island countries between the periods 1994-2018 and 1970-1993. SI refers to Solomon Islands and NC refers to New Caledonia (Source: Deo et al. 2021).

# 4 Future projections of tropical cyclone activity

Earth's climate is a complex system that undergoes significant variability and change as a result of multiple linear and non-linear processes operating at various spatial and temporal scales. This means that past climate trends cannot be simply extrapolated to understand future climate variability and change. Several non-linear processes must be taken into account, along with a range of plausible future greenhouse gas and aerosol concentration scenarios and pathways. Over the past decades global climate models have become the primary tool for making projections over the coming century and beyond. However, the majority of global climate models have a relatively coarse resolution (space between data points is about 150 km) and are unable to resolve changes in TC characteristics (such as frequency and intensity) at island-scale. This substantially limits our ability to understand the effects of projected climate change on TCs over small island countries in the Pacific. Therefore, in this section, our commentary is on the broader Pacific region rather than individual countries.

With a few exceptions, many past investigations have consistently projected a likely decline in TC numbers globally due to future warming, though regional changes can be more variable; see, for example, a recent review by Knutson et al. (2020). In the South Pacific Ocean basin, global climate models, such as those from the Coupled Model Intercomparison Project (CMIP3) experiments, generally project around 5-30% decline in TC numbers by the end of the twenty-first century under greenhouse warming conditions (Tory et al. 2013). In the North Pacific Ocean basin, while TC numbers are generally projected to decline overall, some localised regions – such as near Marshall Islands and Hawaii in the central Pacific – are likely to see increased TC activity due to warming (Murakami et al. 2013).

In a recent study, Chand et al. (2017) used a collection of CMIP5 climate models and sophisticated analysis techniques to show robust changes in regional-scale ENSO-driven TC variability during the twenty-first century (Fig. 8). They showed that TCs become more frequent (~20-40%) during future climate El Niño compared with present-climate El Niño events – and less frequent during future climate La Niña events – around a group of small Pacific Island countries such as Fiji, Vanuatu, Marshall Islands and Hawaii. Their results have important implications for climate change and adaptation pathways for these vulnerable countries.

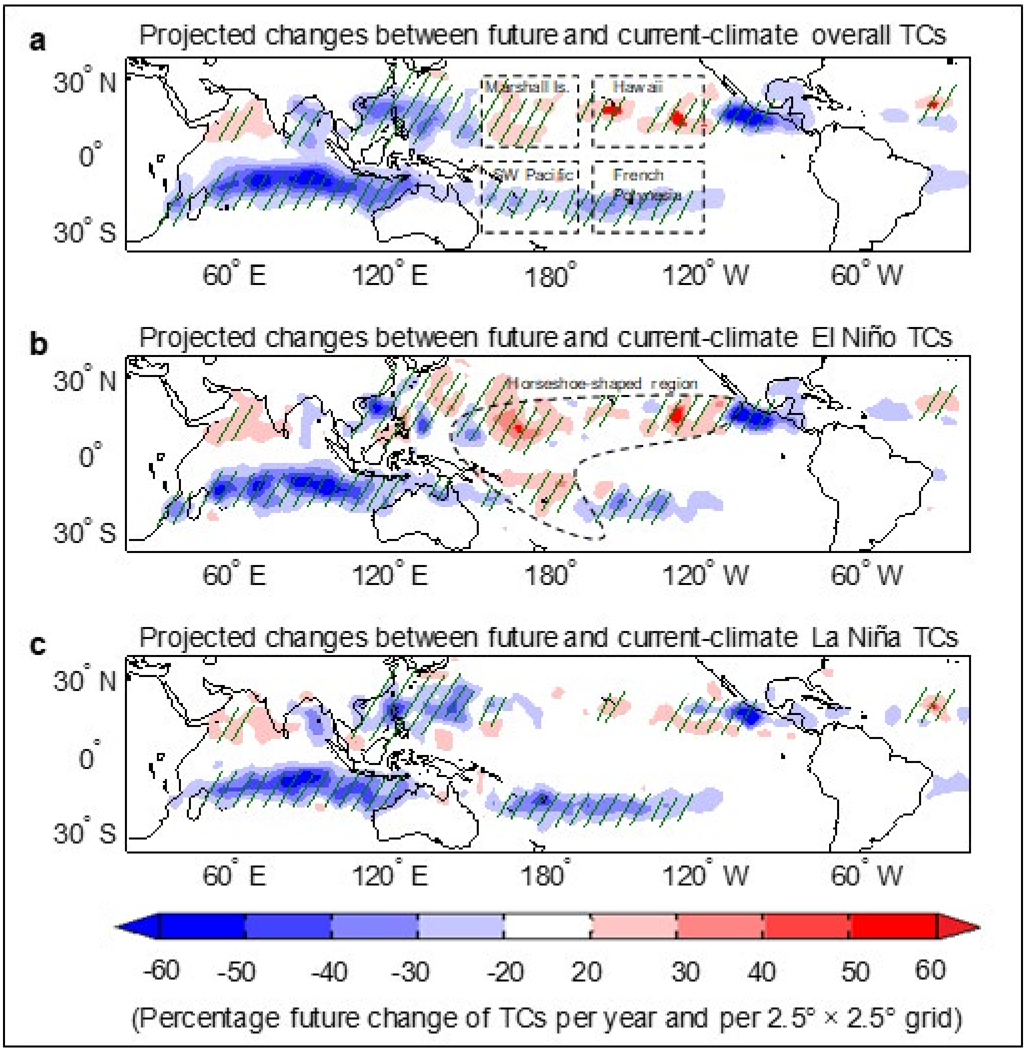


**Figure 8.** Projected changes in tropical cyclone density between the late twentieth century (1970-2000) and late twenty-first century (2070-2100) (a) overall climatology, (b) El Niño years, and (c), La Niña years. Red shading indicates projected increases in tropical cyclone frequency. Stippling denotes changes that are statistically significant at the 95% level. Figure originally from Chand et al. (2017).

Globally, there is a tendency among the higher-resolution models to project an increase in maximum surface wind speeds of TCs (median increase of ~5%) and TC rainfall rate (median projected increase of ~14%) due to anthropogenic global warming (Knutson et al. 2020). In the Pacific Ocean basins both the intensity of TCs and TC-induced rain rate are also projected to increase overall, but the variability between climate model projections can be large, particularly for the southwest Pacific basin. It is anticipated that as more high-quality climate datasets become available in future for the Pacific region through extending the network of long-term observations, uncertainties in higher-resolution climate model projections of TC-related environmental variables can be reduced. This can have implications for more reliable projections of TC characteristics such as intensity and rain rate over Pacific Island nations.

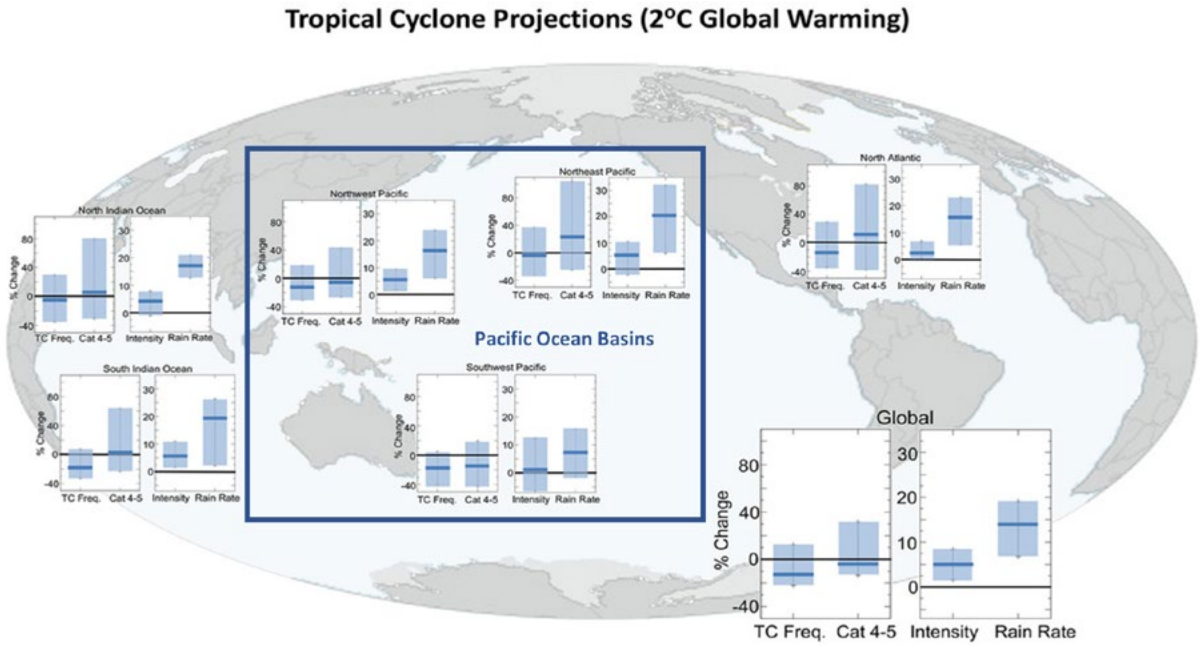


**Figure 9.** TC activity projection for a 2°C global warming (Pacific Ocean basins are highlighted). For each basin, the bars on the left indicate a likely change in the total number of TCs and severe (category 4-5) TCs, and bars on the right indicate likely changes in the average intensity of TCs and associated rainfall. Shown are the median (blue line) and the 10th–90th-percentile ranges (blue bars). (Figure is obtained from Knutson et al. 2020: © American Meteorological Society).

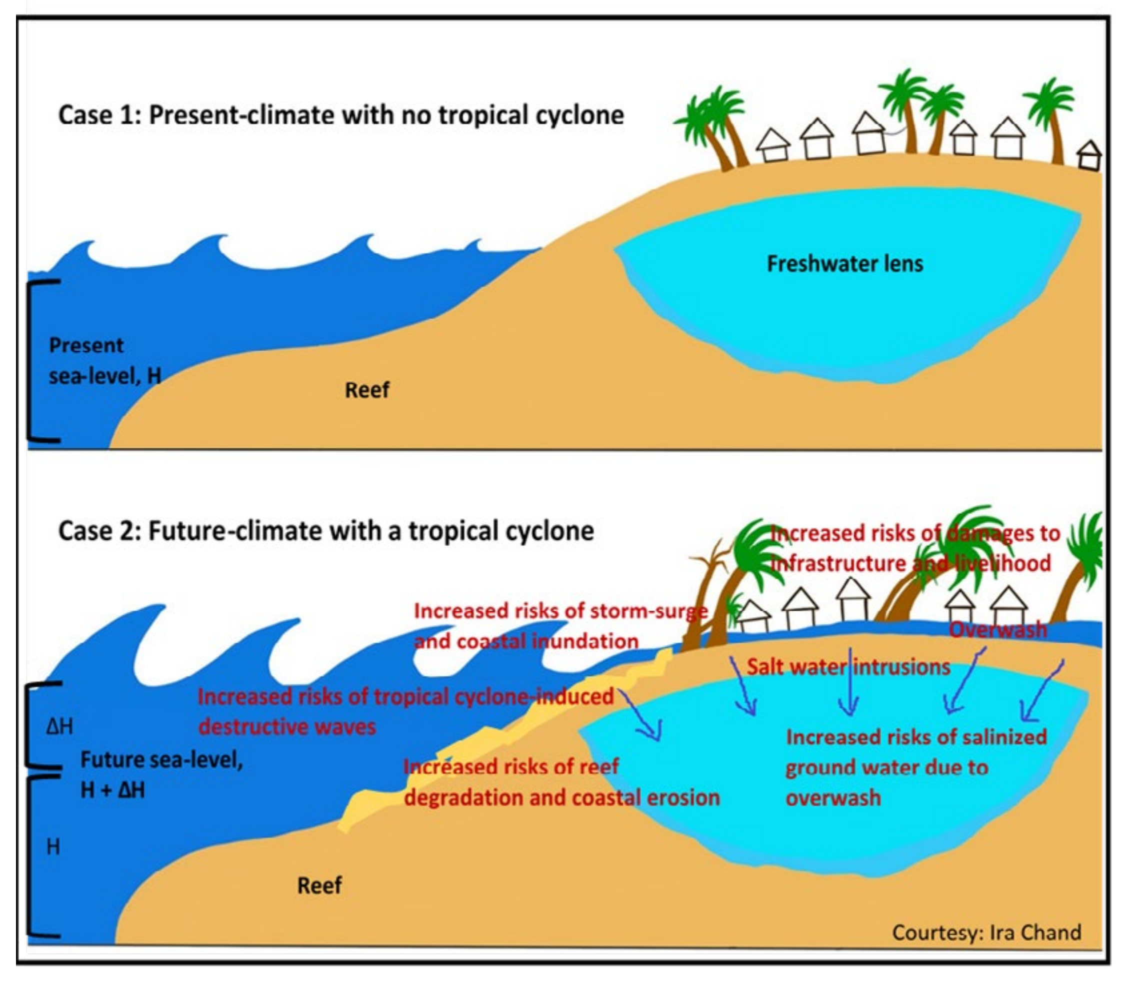
In summary, new research and assessment of evidence suggests that for Pacific Island countries as a whole, the total number of TCs may decrease over the century. However, the decrease is counteracted by likely increase in the projected average intensity of TCs and associated rainfall (Fig. 9). As such, TC impacts on island countries are likely to exacerbate, for example, through greater coastal inundation due to sea level rise and other exposures (see discussions in subsequent sections; reader is referred to CSIRO and SPREP (2021) for details on TC impacts over individual island countries in the Pacific).

# 5 Examples of tropical cyclone impacts

TC occurrences over Pacific Island countries are often accompanied by elevated TC-induced impacts (Fig. 10), in particular those associated with:

- *Wind hazards:* for example, through landfalling TCs.
- *Storm surge:* mainly through strong wind and low central pressure contributions.
- *Destructive waves:* generated by strong winds, even from far-located TCs.
- *Coastal flooding and erosion:* through heavy rain, storm surge and destructive waves.
- *Saltwater intrusion:* through storm-surge over-wash and coastal flooding.
- *Landslides:* through prolonged periods of heavy rainfall.

The extent of impact may differ from country-to-country due to multiple factors including, but not limited to, geographical morphology, level of exposure to TCs, and the adaptive capacity of individual island nations. As discussed earlier, TC exposure can be highly modulated on a year-to-year basis for each country – particularly linked to ENSO – and so the level of TC-induced impact can also vary temporally. For island countries where TC occurrences are enhanced during El Niño years – such as Marshall Islands, Tuvalu, Samoa, Cook Islands and others (Fig. 4) – TC-induced risks can be greatly elevated compared with La Niña years. The opposite is true for countries where TCs are enhanced during La Niña years.



Courtesy: Ira Chand

**Figure 10.** Conceptual diagram of likely changes in TC-induced risks over an atoll country in warming climate for two cases: Case 1 represents a condition in present-climate without any TC, and Case 2 represents a likely condition in future climate in presence of a severe TC event.

The biggest concern for the Pacific Island countries is around the likely changes in TC-induced impacts due to anthropogenic climate change. For example, we know that sea-level rise is already a major problem for PICs (Church et al. 2013; Australian Bureau of Meteorology and CSIRO 2014; CSIRO and SPREP 2021). Projected higher sea-levels are likely to increase the impacts of storm surge, destructive waves and coastal inundation in future warming climate where frequency of severe TCs and associated rainfall are also projected to increase. Increased storm-surge, coastal flooding and destructive waves can greatly elevate the impacts of saltwater intrusion into freshwater aquifers and cultivable land, as well cause coastal erosion, particularly for atoll countries in the Pacific (Fig. 10). Arguably, there is an expectation that global warming may also make TCs more slow-moving (Kossin 2018; Knutson et al. 2020), compounding TC-induced wind hazards and rain rates at local-scale. Figure 11 consolidates results of various past studies to draw a link between warming climate and changing characteristics of TCs, and how such changes may impact PICs in the future.

**Figure 11.** Schematic representation of the linkages between human-induced global warming and TCs (superscripts denote citation number). Note that this diagram is not exclusive and does not quantify the changes, but instead demonstrates how different climatic factors may interact to affect TC characteristics and associated impacts over Pacific Island countries as deduced from past literature.

# 6 Implications for planning and adaptation options

The threats of climate change are very real for PICs even to the extent of rendering some low-lying atoll countries potentially uninhabitable in future (Nurse et al. 2014). While sea-level rise is already a major issue, occasional occurrence of TC-induced impacts substantially aggravates the social, environmental and economic losses for the country. In fact, some of the countries in the Pacific are ranked among top nations in the world requiring the highest protection cost (relative to its gross domestic product) from the increasing threats of global warming (Nurse et al. 2014).

The level of risk associated with a TC event is already enormous for PICs, and TC-induced impacts are likely to exacerbate further as a consequence of anthropogenic climate change. The increasing threats from storm surge and coastal flooding under sea-level rise are of concern in particular for vulnerable low-lying atolls. Such threats can also have direct consequences on long-term food and water security, for example through intrusion of saltwater into freshwater storages and cultivable land, creating irrecoverable damages to the livelihood of local communities and natural resources, and in some cases through permanent loss of islets (Hisabayashi et al. 2017).

In recent decades, damage from TCs – compounded by the effects of climate change and other human-caused stressors – has caused substantial loss of coral coverage in the Pacific region (Beeden et al. 2015). TCs that generate the most damaging waves are those that move slowly, have a large spatial footprint over which high winds occur and are intense. Consequently, it is important to consider not just cyclone intensity, but also size and forward speed. For example, TC *Winston* was not only the most severe historical cyclone in the Southern Hemisphere since official record began but also relatively large and very slow moving. As a result, it had devastating impacts on the island ecosystem and coral reefs in Fiji (Elser 2016). Such impacts have long-term knock-on effects on a country's natural resources such as fisheries, seagrass beds and mangroves which may take several decades to recover.

Climate change adaptation planning for managing future TC-induced impacts can be very complicated for highly vulnerable countries. Regardless, some recent events – such as those associated with severe TC *Pam* and severe TC *Winston* – can present a window of opportunity to trigger transformational changes in the response of local communities to TC-induced impacts. These transformational changes can range from developing quintessential strategies for mitigating immediate impacts of TCs – such as emergency shelters and effective evacuation procedures, to long-term technological and engineering solutions, such as seawalls, levees, desalination plants and storm water harvesting designed to mitigate effects of rising sea-level and storm surges, and their potential impacts on food and water security.

# 7 Next steps

As highlighted earlier, many islands of the Pacific are physically small and low-lying, as well as geographically isolated and surrounded by vast expanses of ocean. They are also highly exposed to natural disasters and extreme weather and climate events such as TCs, storm surges, heavy rainfall, droughts, high winds and large waves. With rising threats from anthropogenic-induced climate change, together with growing coastal settlement and infrastructure development, risks from climate extremes are increasingly likely to worsen. This raises serious concerns around the sustainability of many island nations, noting also their relatively limited capacity to mitigate and adapt to climate change.

There is no one-size-fits-all approach when it comes to developing climate change adaptation and mitigation strategies, particularly for highly vulnerable communities in the Pacific. Drawing on experiences from past TC events as analogies to what may happen in a warming climate will be very useful. Such an activity should emphasise a 'bottom-up' approach that requires local community and stakeholder-led discussion to first determine and evaluate the level of TC-induced threats to critical local factors like food and water security, and then develop relevant and relatable adaptation and mitigation strategies for each factor.

Moreover, developing strategies for adaptation planning processes need to be an iterative process to take into account updated science on climate extremes (Pielke et al. 2012). Adaptation decisions are not static but need to be themselves 'adaptive' to new information and knowledge as it becomes available. Moving forward, it is critical that relevant national agencies (such as Meteorological Services, National Disaster Management Offices and Departments of Climate Change) understand the differences in the likelihood of TC occurrence between different climatic conditions (e.g., El Niño and La Niña periods) and clearly communicate this to sector stakeholders and the wider community through their information products and awareness raising. Such approaches are believed to be a more inclusive way of assessing impacts of TCs and adopting more effective adaptation methodologies to deal with the complexity of potential extreme events affecting Pacific Island nations.

While contributions of past studies are substantial, more work is still needed to better quantify the impacts of natural climate variability and climate change on Pacific TCs. The use of synthetic tropical cyclone tracks for estimating climate change impacts on Pacific Island nations is another promising avenue of research. Important information, data gaps and many uncertainties still exist in different metrics used to evaluate impacts of TCs on small islands. It is anticipated that as longer temporal records of updated TC data, as well as new generations of climate models become available, our level of confidence in TC projections will improve, better informing adaptation planning and implementation processes for PICs.

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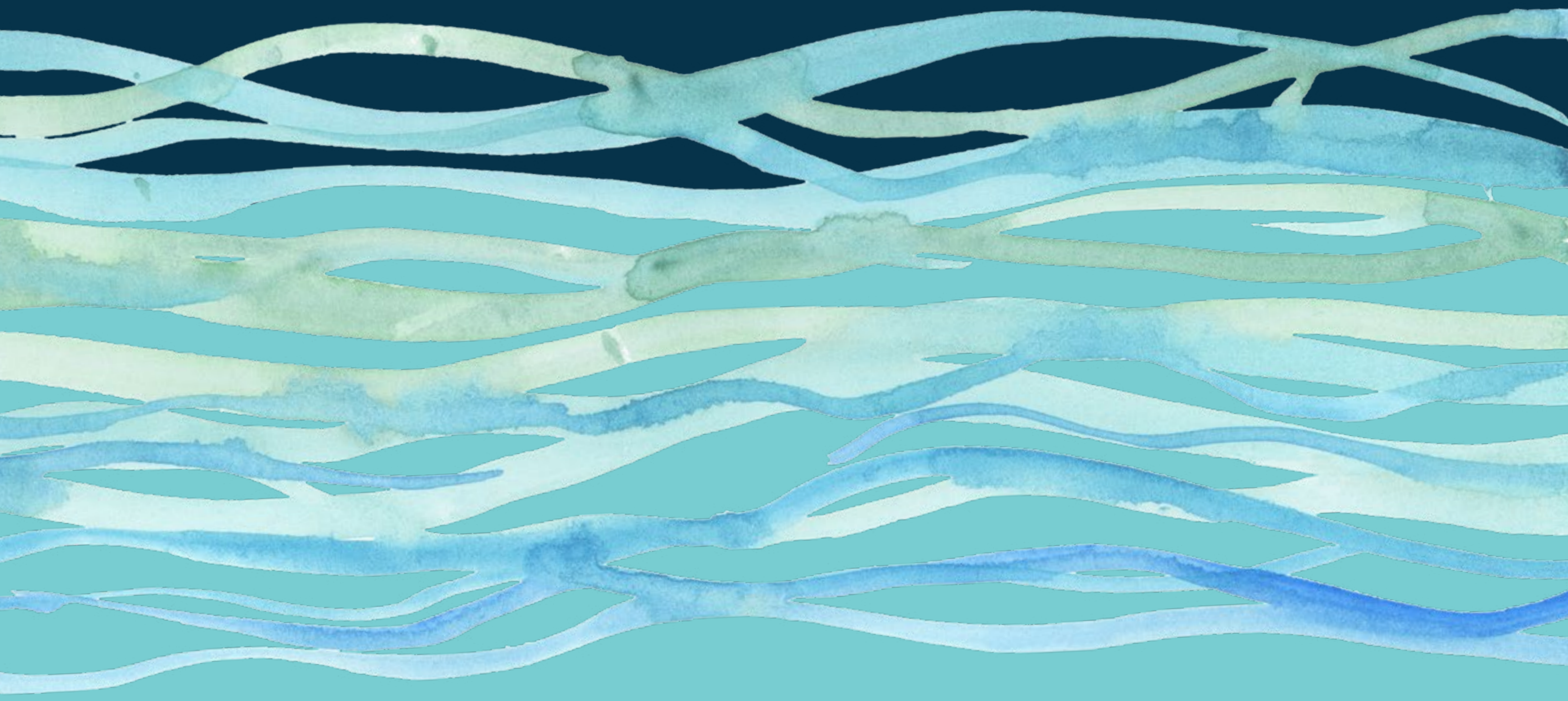

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