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REVIEW ARTICLE

Climate processes and drivers in the Pacific and global warming: a review for informing Pacific planning agencies

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Abstract

Pacific Island countries are vulnerable to climate variability and change. Developing strategies for adaptation and planning processes in the Pacific requires new knowledge and updated information on climate science. In this paper, we review key climatic processes and drivers that operate in the Pacific, how they may change in the future and what the impact of these changes might be. In particular, our emphasis is on the two major atmospheric circulation patterns, namely the Hadley and Walker circulations. We also examine climatic features such as the South Pacific Convergence Zone and Intertropical Convergence Zone, as well as factors that modulate natural climate variability on different timescales. It is anticipated that our review of the main climate processes and drivers that operate in the Pacific, as well as how these processes and drivers are likely to change in the future under anthropogenic global warming, can help relevant national agencies (such as Meteorological Services and National Disaster Management Offices) clearly communicate new information to sector-specific stakeholders and the wider community through awareness raising.

Keywords Pacific Island countries · Climate variability and change · Atmospheric circulations

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1 Introduction

Most Pacific islands are relatively small, and many are low-lying, geographically isolated and surrounded by vast expanses of ocean. They are also highly exposed to natural disasters and extreme climatic events such as tropical cyclones, storm surges, extreme rainfall and flooding, droughts, high winds and large waves. The threats posed by these hazards can vary markedly from place-to-place and year-to-year due to effects of various climatic processes and drivers that operate on different spatial and temporal scales. Furthermore, with anthropogenic climate change and growing coastal settlements and infrastructure development, future risks from climate extremes are expected to increase (IPCC 2021). This raises serious concerns around the sustainability of some island nations, owing to their limited capacity to adapt to climate change.

Over the past decades, substantial progress has been made to obtain better insights on the influence of anthropogenic climate change on key ocean and atmospheric processes. It is now imperative that such new and up-to-date information is reviewed and consolidated to better inform high-priority adaptation needs of the Pacific Island nations. In this paper, we provide an overview of the main atmospheric circulation features, climate processes and drivers that operate in the Pacific and have substantial effects on extreme climatic events. We also discuss how these processes and drivers are likely to change in the future under anthropogenic global warming. It is important to note that while this review covers some of the main features related to the mean climate and some extremes such as tropical cyclones, it does not cover other drivers and processes important in the Pacific such as global drivers of sea-level rise. Regardless, it is anticipated that this review can help relevant national agencies (such as Meteorological Services and National Disaster Management Offices in the Pacific) clearly communicate new information to sector-specific stakeholders and the wider community through awareness raising.

2 Global atmospheric circulation

The Hadley and Walker circulations are the two main overturning atmospheric circulations in the tropics (Fig. 1). They have wide-ranging effects on weather patterns and climate conditions across the Pacific (e.g. Held (2019)), and so understanding characteristic changes in these circulations is imperative for science and society.

2.1 The Hadley circulation

The Hadley circulation is a thermally driven overturning circulation within the tropics and aligned north–south with rising air near the equator due to intense solar heating and descending air in the subtropics. This circulation drives winds towards the equator near the surface. These winds converge near the equator, the air then ascends to feed poleward, recirculating winds higher up in the troposphere. The Hadley circulation provides a mechanism to transport heat poleward to the subtropics (~30° latitudes). The surface winds contribute to the equatorward component of the trade winds, which blow from the subtropics towards the equator.

Severe convective systems such as tropical cyclones and thunderstorms are frequently spawned within the ascending branch of the Hadley circulation, particularly during the

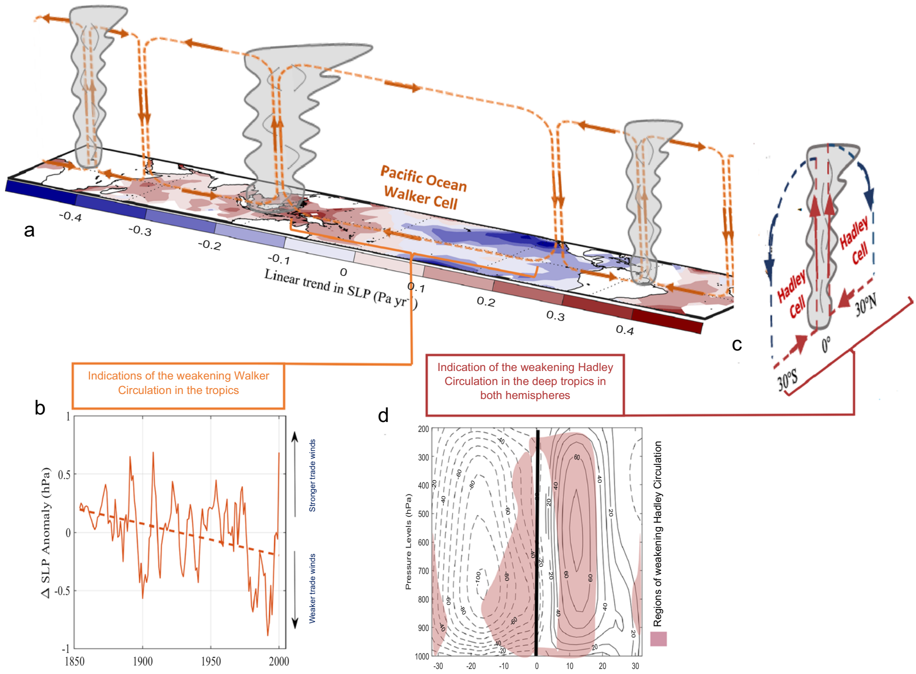

Fig. 1 Schematic representations of the Walker and Hadley circulations and associated changes during the twentieth century. (**a**) Linear trends in sea-level pressure (SLP) and the three Walker cells (in orange). (**b**) Changes in the Indo-Pacific SLP gradient since the mid-nineteenth century. (**c**) An illustration of the Hadley circulation. (**d**) Observed Hadley circulation pattern, represented by mass streamfunction of the zonal mean meridional winds (positive contour values indicate clockwise and negative contour values indicate anticlockwise circulations), during the twentieth century (red shadings indicate regions where the summertime mean intensity of the circulation has weakened significantly relative the pre-1900 period)

summer months of the two hemispheres (i.e. December-February for the Southern Hemisphere and June–August for the Northern Hemisphere) when the strength of the Hadley circulation and the associated ascending air in the deep tropics are more intense compared with their respective winter months. The Hadley circulation varies in association with the El Niño-Southern Oscillation (ENSO). ENSO is a naturally occurring phenomenon centred in the tropical Pacific and can be explained in terms of three different phases: (i) El Niño, (ii) a neutral phase and (iii) La Niña (see Sect. 4 for details on ENSO phenomenon). During El Niño events, the Hadley circulation tends to contract towards the equator, whereas during La Niña, it tends to expand.

Over the past decades, results from observations and model simulations indicate that the Hadley circulation has widened (i.e. undergone poleward expansion) considerably in both hemispheres (Hu et al. 2018; Power et al. 2021). The expansion of the Hadley circulation is sometimes referred to as an expansion of the tropics. Climate model experiments, such as those from the World Climate Research Programme's Coupled Model Intercomparison Project (WCRP-CMIP), further indicate that the widening trend is likely to continue as the concentration of greenhouse gases further increases in the atmosphere, but there is no general agreement on the changes in the intensity of the Hadley circulation (Hu et al. 2018; Power et al. 2021). A study by Grise et al. (2019) provides a comprehensive review of past studies on tropical expansion and consolidates discrepancies noted in the literature using updated information and consistent analysis. In particular, their study showed that anthropogenic forcing played a significant role in the poleward shift of the Southern Hemisphere tropical edge during the second half of the twentieth century, while in the Northern Hemisphere, the shift was not significant for the same period due to large natural variability. Their study also indicated that the change in the phase of the Pacific Decadal Oscillation (PDO) from positive to negative during the late 1990s contributed to tropical expansion over the last 30 years.

Strengthening of the Hadley circulation has been noted over the past two decades, but it is argued that this trend is linked to interdecadal climate variability (e.g. England et al. (2014); Hu et al. (2018)). On the longer timescale, the Hadley circulation is expected to weaken, in addition to being widened, due to greenhouse global warming as consistently demonstrated by climate model historical and projection simulations (e.g. Hu et al. (2018)).

Such changes in the mean state of the Hadley circulation can have huge implications for the severe climatic events in the Pacific. For example, tropical cyclone formation regions, as well as the location of tropical cyclone maximum intensity, are likely to shift poleward due to tropical expansion (Sharmila and Walsh 2018). Consequently, this may expose several higher-latitude island nations to catastrophic winds and storm surge events in the future. The weakening of the Hadley circulation can also imply fewer tropical cyclones (e.g. Chu et al. (2020); Chand et al. (2022)) as such changes can manifest as a reduction of the upward mass flux in the ascending branches of this circulation where substantial tropical deep convection occurs (for example, see Fig. 1). Moreover, the edges of the tropical belts are the outer boundaries of the subtropical dry zones and their poleward shift could lead to potential effects on natural ecosystem, agriculture and water resources (Seidel et al. 2008).

2.2 The Walker circulation

The Walker circulation is the east–west component of the tropical circulation, which is driven by the sea-level pressure gradient force (and associated sea surface temperature gradient) between the western and the eastern Pacific. The main Walker cell is in the Pacific Ocean (hereafter referred to as the Pacific Walker cell) with ascending air normally over the maritime continent (i.e. the region between the Indian and Pacific Oceans including the archipelagos of Indonesia, Borneo, New Guinea, the Philippine Islands, the Malay Peninsula, and the surrounding seas) and descending air in the eastern Pacific. Two secondary cells are located over South America and Africa with compensating subsidence over the Atlantic Ocean and the Indian Ocean, respectively. The “trade” winds near the surface and west–east upper-level winds complete the circulation in each cell. Moist air rises and feeds convection, whereas dry air from the upper troposphere sinks. The main Walker cell contributes to the strength of the east–west component of the trade winds over the Pacific.

The Pacific Walker cell also varies from year-to-year in association with ENSO. During El Nino years, the Pacific Walker cell tends to weaken, and the ascending branch of the Walker circulation shifts farther eastward into the central-eastern Pacific from its normal location with descending branches over the maritime continent and the South American coast. The opposite occurs during La Niña years: the Walker circulation strengthens, the ascending branch of the Walker circulation is pushed deep into the maritime continent and the descending branch occurs in the eastern Pacific.

Studies have shown that during the twentieth century, the Walker circulation weakened due to increasing greenhouse warming (e.g. Vecchi et al. (2006); Power and Kociuba

(2011); Kociuba and Power (2015)). However, since the early 1980s, the Walker circulation—like the Hadley circulation—strengthened (Kociuba and Power 2015; Power et al. 2021). While some studies have attributed this strengthening to anthropogenic warming (e.g. Seager et al. (2019)), others argue that such changes are short-term and are largely due to internal climate variability (England et al. 2014; Chung et al. 2019; Kociuba and Power 2015). Previous and current generations of climate models generally simulate a weaker Walker circulation over the coming century due to increasing greenhouse warming (e.g. Power and Kociuba (2011); Kociuba and Power (2015); Chung et al. (2019); Power et al. (2021)), as well as a shift eastward (Bayr et al. 2014). Under these circumstances, expectations are for enhanced convective activity, such as tropical cyclones, to occur farther east into the central Pacific (such as near Hawaii) and suppressed activity elsewhere in the Pacific (e.g. Murakami et al. (2013); Chand et al. (2017)). However, given the inability of climate models to simulate the magnitude of the recent strengthening, confidence in the projected weakening is low (e.g. Kociuba and Power (2015)).

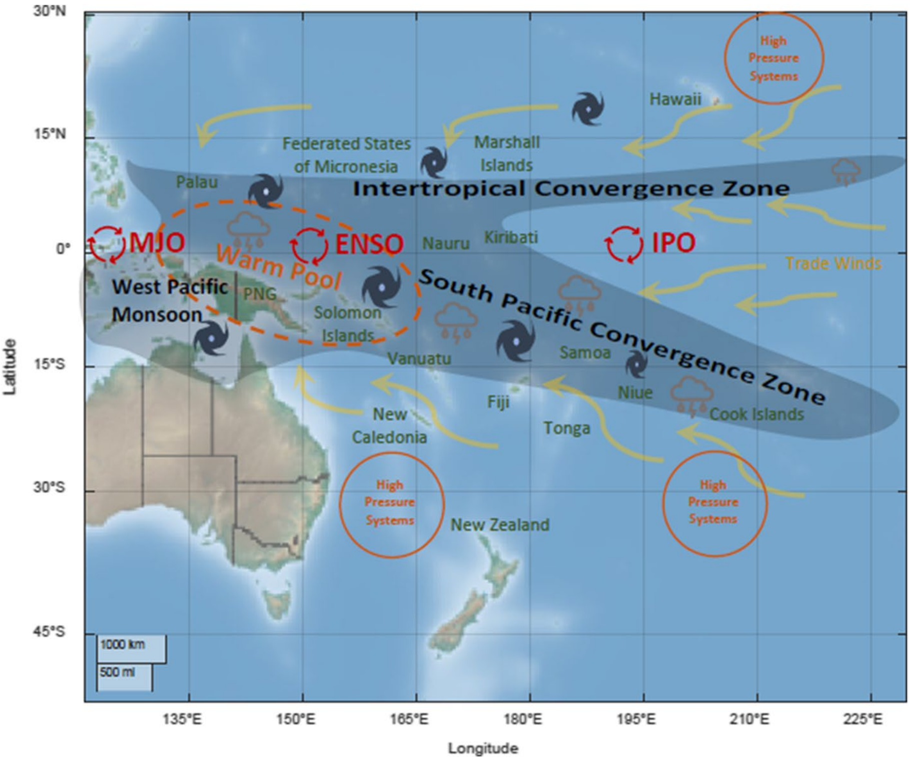

Fig. 2 Schematic representation of major climatic features and drivers in the Pacific. The Intertropical Convergence Zone (ITCZ), South Pacific Convergence Zone and West Pacific Monsoon are characteristic features where convective activities such as tropical cyclones and thunderstorms are frequently spawned. The Madden–Julian Oscillation (MJO), El Niño-Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation are the three main modes of climate variability that operate across the Pacific at intraseasonal, interannual and interdecadal timescales, respectively

3 Convergence zones in the Pacific

Climate in the tropical and subtropical Pacific is dominated in many places by the two most extensive features of the global atmospheric circulation in the Pacific: the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ) (BoM-CSIRO 2011). Both these features merge with the West Pacific Monsoon (WPM) in the maritime continent region. Deep tropical convection such as tropical cyclones and depressions, thunderstorms and associated rainfall is frequently spawned within these features (Fig. 2). Here, we provide an overview of the ITCZ and SPCZ in the context of current climate and how they may change in the future due to anthropogenic greenhouse warming. Note the WPM is part of the broader Asian-Australian Monsoon system. This system moves seasonally from the Northern Hemisphere across the equator into the tropical regions of the Southern Hemisphere during December-February. It is typically responsible for marked seasonal changes in rainfall and winds, and can also affect climate in countries like Kiribati, Marshall Islands, Nauru, Palau and Papua New Guinea, although in Nauru and the Marshall Islands, the influence of the WPM only occurs in some years (BoM-CSIRO 2011). The WPM is responsible for marked seasonal rainfall variability as well.

3.1 Intertropical convergence zone

In the previous section, we noted that the Hadley cell converges near the equator. More specifically, it converges in the ITCZ (also recognised as the meteorological equator). The ITCZ is identified as a tropical belt of deep convective clouds (Waliser and Gautier 1993) or as the maximum in the mean rainfall (Philander et al. 1996). In the Pacific, the ITCZ lies just north of the equator and influences climate in countries such as the Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau and Papua New Guinea.

Climatologically, the mean location of the ITCZ in the Pacific Ocean is confined to the Northern Hemisphere in both boreal summer and winter owing to global energy redistribution through meridional overturning circulation whereby heat is transported from the Northern Hemisphere to the Southern Hemisphere, but the moisture from the Southern Hemisphere to the Northern Hemisphere, pushing the tropical rainband north (e.g. Frierson et al. (2013)). However, the seasonal migration of the ITCZ is more dramatic over the Indian Ocean and the WPM region where the ITCZ swing can be between average latitudes of 20° N in boreal summer and 8° S in boreal winter, prompting the seasonal rainfall variations of the South Asian monsoon (e.g. Liu et al. (2020)). On year-to-year timescales, ENSO substantially modulates the mean position of the ITCZ in the eastern Pacific where the ITCZ draws even closer to the equator during El Niño compared to during La Niña or neutral events (e.g. Liu et al. (2020)).

Over recent decades, satellite rainfall observations and reanalysis data, as well as climate model simulations, demonstrate the narrowing of the ITCZ width due to warming (e.g. Lau and Kim (2015)). Further narrowing is also expected in future climate under increased warming due to likely changes in the moist statistic energy budget in the tropics (Byrne and Schneider 2016). However, the mean location of the ITCZ has remained relatively unchanged (Byrne et al. 2018). The net ascent within the ITCZ has weakened over recent decades and is expected to weaken further as the climate continues to warm (Byrne et al. 2018), consistent with a weakening of the Hadley circulation. It is important to note that this net weakening is due to strongly reduced ascent on the equatorward edge of the ITCZ. While the tropical Pacific has warmed, the cold tongue on the equator has not (e.g.

Seager et al. (2019), (2022)). This change in meridional sea surface temperature (SST) gradient would favour a northward migration of the ITCZ or weakening of the ITCZ on its southern flank. It is important to note that the overall ascent within the core of the ITCZ has increased due to warming, and so its precipitation rate has intensified overall (Byrne et al. 2018).

3.2 South Pacific convergence zone

The SPCZ spans the southwest Pacific Ocean, extending quasi-zonally from the maritime continent in the tropics and then diagonally east-southeast in the subtropical regions towards French Polynesia. The SPCZ affects climate of the South Pacific Island countries such as the Cook Islands, Fiji, Nauru, Niue, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu, and Kiribati in some years (BoM-CSIRO 2011; Brown et al. 2020). The SPCZ is more active during the austral warm season (i.e. November–April, also known as the “wet season”). Like the ITCZ, the SPCZ also merges with the WPM in the maritime continent region.

During the austral summer season, the SPCZ delivers considerable rainfall, as well as other convective weather systems such as tropical cyclones and thunderstorms, to the South Pacific Island countries (e.g. Brown et al. (2020)). On interannual timescales, the SPCZ is substantially modulated by ENSO. During El Niño years, the SPCZ and associated convective activity typically shift northeastward, while during La Niña years, it tends to move southwest (Folland et al. 2002). During very strong El Niño events, the SPCZ moves thousands of kilometres closer to the equator and sometimes merges with the ITCZ to form a single east–west band of rainfall, resulting in the loss of its diagonal orientation (e.g. Chung and Power (2015)). At longer timescales, the Interdecadal Pacific Oscillation (IPO) causes large decadal and multi-decadal variations in the mean location of the SPCZ (e.g. Salinger et al. (2001); (Folland et al. 2002)). During positive IPO phases, the SPCZ shifts northeastward as it does in El Niño years and shifts southwestward during negative IPO phases as in La Niña years (see Sect. 4 for details on the IPO).

Over the past decade, considerable effort has been made towards understanding the likely impacts of climate change on the location, intensity and variability of the SPCZ. However, analysis of reliable historical records (such as rainfall) for the South Pacific countries since the mid-twentieth century reveals no significant trends in the characteristics of the SPCZ. This might be due to the presence of large naturally occurring decadal to multi-decadal variability that makes detection of any likely “trends” from relatively short-term data records challenging (Brown et al. 2020). Therefore, assessment of the impact of global warming on the SPCZ relies heavily on climate model projections such as those from the Climate Model Intercomparison Projects (CMIP). Simulation of the SPCZ is also challenging as most CMIP models can erroneously make the SPCZ too zonal and extend too far eastward, sometimes referred to as the “double ITCZ”. CMIP simulations generally indicate no consistent change in the mean SPCZ location (Brown et al. 2020).

From a suite of CMIP model experiments, Widlansky et al. (2013) showed the two competing mechanisms for the SPCZ rainfall in response to global warming: “wet gets wetter” and “warmest gets wetter”. Mean specific humidity is projected to increase over the entire tropical Pacific in response to greenhouse warming. Even though the simulated moisture increase in the SPCZ region is weaker than along the equator, it is substantially greater than that in the southeast Pacific, a region that warms least and where drying is projected by nearly all climate models (Brown et al. 2012). This mechanism is referred to as the "wet gets wetter" thermodynamic response to greenhouse warming (that is, the SPCZ region gets wetter compared to regions in the southeast Pacific). On the other hand, the SPCZ region experience relatively minor warming than those near the equator or the ITCZ. This causes anomalous divergence of mean moisture away from the SPCZ region and towards the warmest waters near the ITCZ. The corresponding anomalous circulation results in the increased rainfall within the ITCZ region typically located north of the equator (that is, a "warmest gets wetter" dynamic response). As such, while some islands in the SPCZ region could see a rainfall increase if temperatures rises high enough, those that lie along the southeast margin of the SPCZ would experience drying.

4 Key drivers of natural climate variability

Natural climate variability affects weather and climate across the Pacific region. Climate variability modulates the ITCZ and SPCZ, and risks are associated with extreme events including flood, drought and tropical cyclones (e.g. Chand and Walsh (2010); Iese et al. (2021)). In the Pacific, three key sources of climate variability are the Madden–Julian Oscillation (MJO), ENSO and the IPO. The MJO drives variability within seasons (e.g. Zhang (2005)), ENSO drives variability from year-to-year (e.g. Trenberth (1997)) and the IPO drives variability from decade-to-decade and generation-to-generation (Power et al. 1999; 2021). Here, we provide an overview of the MJO, ENSO and IPO, and we discuss some of their impacts in the Pacific.

4.1 Madden–Julian Oscillation

The MJO is the dominant mode of intraseasonal (30–90 days) variability in the tropics (see a review by Zhang (2005)). It comprises deep convective activity—flanked by regions of suppressed convective activity—that is initiated in the tropical Indian Ocean and slowly propagates eastward at $\sim 5\ \mathrm{m\ s^{-1}}$ into the tropical Pacific region. The MJO undergoes a strong seasonal cycle in both its strength and location. During the austral warm season (i.e. November–April), the MJO is primarily more active south of the equator. The secondary peak season is in the boreal summer when the MJO signal is strong north of the equator.

Since its discovery in the 1970s (Madden and Julian 1971), the crucial role of the MJO in affecting hydrological cycles and high-impact weather and climate extremes has been well recognised. The MJO substantially modulates rainfall (and extreme rainfall) across the Pacific Island nations (e.g. Deo et al. (2021)). It also has a substantial impact on tropical cyclones. For example, as the MJO propagates across the tropical South Pacific, not only is the rainfall activity within the SPCZ region enhanced (Haffke and Magnusdottir 2013; Deo et al. 2021) but the frequency and intensity of tropical cyclones increase as well (e.g. Chand and Walsh (2010); Ramsay et al. (2012)). Due to its quasiperiodic occurrence at the intraseasonal timescales, the MJO provides a primary source of predictability for extended-range weather forecasts in the Pacific, and elsewhere around the globe, and thereby fills the gap between short-term deterministic forecasts and long-term climate predictions which may be beneficial to fisheries sustainability for Pacific Island nations (e.g. Dunstan et al. (2018)) and other applications (White et al. 2017).

Given the strong dependence of MJO dynamics on the mean climate state (e.g. Jiang et al. (2020)), it is natural to expect that MJO characteristics and associated impacts are likely to change in a warming climate. Some studies using climate model experiments have shown that the frequency of MJO events and eastward propagation speeds are likely to increase with increasing greenhouse gas emissions (Arnold et al. 2015). Also, regions with preferential SST warming in the future (such as the eastern tropical Pacific, Xie et al. 2010) may result in proportionally greater increases in the MJO-related precipitation, though the tendency for models to preferentially warm the eastern Pacific does not yet have observational support (Coats and Karnauskas 2017).

4.2 The El Niño-Southern Oscillation

ENSO is the major mode of year-to-year climate variability in the Pacific (McPhaden et al. 2006, 2020). The ENSO cycle is irregular, and most of its variability has periods of between 2 and 7 years (e.g. Trenberth (1997)). The term "El Niño", which is Spanish for "The Boy" or "The Christ Child", was traditionally used to refer to the annual occurrence of a warm ocean current that flowed southward along the west coast of Peru and Ecuador around Christmas time. Scientists later realised that El Niño is far more than a coastal phenomenon; it is associated with basin-scale warming of the tropical Pacific Ocean. Today, the term "El Niño" is commonly used to refer to the occurrence of anomalously warm SSTs in the central and eastern equatorial Pacific Ocean every few years. The opposite "La Niña" ("The Girl" in Spanish) consists of large-scale cooling of the tropical central-eastern Pacific. This anomalous warming and cooling of the central and eastern equatorial Pacific SST occur in sync with the atmospheric phenomenon called the Southern Oscillation (Walker 1928) which is characterised by a seesaw in tropical sea-level pressure (SLP) between the Western and Eastern Hemispheres (e.g. Trenberth and Shea (1987)). During El Niño, the SLP falls in the central and eastern Pacific and rises in the western Pacific; the reverse occurs during La Niña. El Niño and the Southern Oscillation are two coupled aspects of the same phenomenon, classically explained through positive feedback between ocean and atmosphere in the equatorial Pacific (Bjerknes 1966, 1969). The zonal atmospheric circulation (i.e. east–west circulation) that arises as a result of this coupling is called the "Walker circulation", which also varies during ENSO.

The effects of ENSO on various weather and climate variables are not only confined to the equatorial Pacific but are also observed in many parts of the world (see review by Taschetto et al. (2020)). Numerous indices have been developed to monitor the status of ENSO (e.g. Trenberth and Stepaniak (2001)). The two most commonly used indices are called the Southern Oscillation index (SOI) and the Niño3.4 index. The SOI is calculated using the barometric pressure difference between Tahiti and Darwin (Troup 1965). A strong, persistently negative SOI is typical of El Niño conditions, while a strong and persistently positive SOI is indicative of La Niña. Similarly, the Niño3.4 index measures the SST anomaly in the central and eastern Pacific (5°N-5°S; 170°W-120°W). A strong, persistently positive Niño3.4 index indicates an El Niño event. Note that SOI and Niño3.4 index change almost simultaneously, indicative of strong ocean-atmospheric coupling during ENSO events.

Over the past years, another type of El Niño—referred to as the "El Niño Modoki" (Ashok et al. 2007)—has been observed. Unlike traditional El Niño events, El Niño Modoki events have above-normal SSTs that are confined more to the central Pacific region flanked by below-normal SSTs on the eastern and western sides. Some scientists hypothesise that this might be related to anthropogenic global warming (e.g. Yeh et al. (2009); McPhaden et al. (2020)), and if so, then this type of El Niño may become more frequent in the future.

As ENSO is the dominant mode of interannual natural climate variability in the Pacific, any substantial change in the character of ENSO in response to anthropogenic global warming will have major implications on the regional climate of the small island countries in the Pacific. Past studies provide some indications of projected future changes in certain aspects of ENSO using current-generation climate models (see, for example, a comprehensive review by Cai et al. (2021)). This includes an increase in ENSO-related SST variability and a corresponding increase in the frequency of extreme El Niño events (e.g. in 1982/83 and 1997/98) (Cai et al. 2014), an increase in the intensity of ENSO-driven precipitation variability over much of the Pacific (Power et al. 2013) and shift eastward leading to an eastward intensification of extratropical teleconnection (Cai et al. 2021) and a potential increase in the frequency of the "Modoki-type" central Pacific El Niños (Kim and Yu 2012; Power et al. 2013).

However, it is important to note that there is a large degree of inconsistency among climate models on some aspects of future projections (e.g. Collins et al., (2010); Power et al. (2021)), and so care must be exercised when interpreting climate change projection results. Regardless, there is a strong consensus that ENSO variability will continue to dominate regional-scale climate in the future (Power et al. 2013; McPhaden et al. 2020), and strongly influence weather-related variables such as drought and rainfall in the changing climate (e.g. Stevenson et al. (2012); McPhaden et al. (2020); Iese et al. (2021)).

4.3 Interdecadal Pacific Oscillation

Climate in and around the Pacific Ocean also shows a variability on decadal and interdecadal time scales (e.g. Mantua et al. (1997); Power et al. (1999); Power et al. (2021)). Much of this variability has been linked to the Pacific Decadal Oscillation (PDO, Mantua et al. 1997) and the IPO (Power et al. 1999). The PDO can be regarded as the North Pacific expression of the near-global scale decadal variability (see a review by Newman et al. (2016)). It is the result of a combination of different physical processes, operating locally and remotely on different time scales and spanning tropics and extratropics. One particular pattern of the ENSO-like variability, the IPO, is often compared to the PDO, noting that IPO and PDO are not identical (e.g. Newman et al. (2016)). When the IPO is in a positive phase, SST in the central and eastern Pacific (i.e. approximately east of the date line) is high, whereas the opposite is true during negative phases of the IPO. Most recently, a South Pacific decadal oscillation (SPDO) has also been described (Chen and Wallace 2015; Lou et al. 2021). The SPDO characterises the Southern Hemisphere contribution to the Pacific-wide IPO and is analogous to the PDO centred in the North Pacific.

The IPO is associated with a waxing and waning of the impact of ENSO on the Pacific (e.g. Salinger et al. (2001)). For example, the rapid shift from negative to positive IPO during the mid-1970s was associated with a shift to an El Niño–dominated period, whereas the shift to a negative IPO around the year 2000 was associated with a La Niña–dominated period. It is important to note that IPO presents only a few realisations in the observational record and so the extent to which it modulates ENSO teleconnections is not clear. While the IPO and PDO are thought to be partially driven by random changes in ENSO activity from decade-to-decade (Power and Colman 2006; Power et al. 2021), they are also thought to be real dynamic features of the climate system (Holbrook et al. 2014). However, full understanding of the causes of the IPO and the PDO has not yet been provided. Separately, and most recently, it has been found that the Pacific-South American (PSA) mode provides potential predictability to the SPDO and ENSO several seasons in advance (Lou et al. 2021). The extent to which IPO-driven (and PDO-driven) variability can be predicted is the subject of ongoing research (Power et al. 2021). The reasons behind different IPO phases being associated with different impact are also not yet fully understood, with some studies suggesting that the synergetic match of positive IPO and El Niño would magnify the typical IPO/ENSO impacts on climate, whereas the opposite phases (i.e. negative IPO and La Niña) would weaken the impact (e.g. Gershunov and Barnett (1998)).

Given the limited degrees of freedom associated with historical record of IPO, climate models can provide the best hope for establishing synergistic links between ENSO and IPO modes of variability in both historical and future climates. However, for this to occur, a realistic balance of IPO (and PDO-driven) processes must be simulated realistically in climate models. At present, it appears that the current generation of models underestimates the tropical forcing of the PDO in the North Pacific Ocean (e.g. Newman et al. (2016)). Regardless, it is anticipated that new generation of climate models (such as those from CMIP6 experiments) may provide more clarity on the PDO- and ENSO-related changes in regional climate, ecological, and socioeconomic impacts (for example, see a review by Newman et al. (2016)).

4.4 Tropical Pacific decadal variability

While the IPO is the Pacific-wide manifestation of interdecadal variability that includes the tropics and midlatitudes, the tropical component of this variability takes the form of the "ENSO-like" shifts between periods of positive (El Niño) and negative (La Niña) states. This phenomenon, which to some degree is due to residuals of the high-frequency modes like ENSO in the tropics (Power and Colman 2006), is referred to as tropical Pacific decadal variability". The term "Tropical Pacific Decadal Variability" (TPDV) has been used to refer to variability and change in the tropical Pacific that occurs on decadal timescales (Power et al. 2021). This includes naturally occurring internal variability that arises from instabilities in the climate system, as well as the response to external forcing that causes changes to Pacific climate that unfold on decadal and longer timescales (Power et al. 2021). Both natural (e.g. solar variability or volcanic eruptions) and anthropogenic (e.g. greenhouse gases and aerosols) forcing can contribute to TPDV (Power et al. 2021).

Presently, there is still a great deal of uncertainty about the causes of TPDV and the accuracy to which it can be simulated and predicted (Power et al. 2021). According to this study, the relative contribution of external TPDV is considerably larger in the western Pacific, where the global anthropogenic warming signal is dominant over weak background natural variability signal; internal TPDV dominates in the central Pacific and in off-equatorial bands in the eastern part of the basin, especially in the Northern Hemisphere.

4.5 Natural variability vs forced changes

We know, for example, that the warming in the west Pacific is driven by increases in greenhouse gas concentrations and that the warming is so great that temperature variability over the west Pacific Ocean is now beyond the envelope of natural variability experienced prior to the mid-1970s (Wang et al. 2016; Power et al. 2021). This warming has markedly increased the likelihood that Pacific Island countries will experience unprecedented high monthly temperatures (Power and Delage 2019). Unfortunately, more record-setting heat events will occur over coming decades, even if the net global greenhouse gas emissions are markedly reduced (Power and Delage 2019). This is because the benefits of markedly reducing emissions are not evident until closer to the mid-twenty-first century (IPCC 2021). Nonetheless, it is important to note that while tropical Pacific strongly modulates regional climates and their variability globally, its response to rising greenhouse gases can be controversial. For example, as highlighted in Section 2.1, current-generation climate models predict that rising greenhouse gases reduce the west-to-east warm-to-cool sea surface temperature gradient across the equatorial Pacific, but observational records show strengthening of the gradient over the recent decades (Seager et al. 2019, 2022; Watanabe et al. 2021). Such inconsistencies can have implications on future projections of climate variables in the tropical Pacific region.

5 Summary

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 climatic hazards and extreme events such as tropical cyclones, storm surges, extreme rainfall, droughts, high winds, marine heatwaves and erosion and safety issues from significant wave events. With rising threats from anthropogenic climate change, together with growing coastal settlement and infrastructure development, risks from climate extremes are expected to increase. This raises serious concerns around the sustainability of many island nations, owing to their limited capacity to mitigate and adapt to climate change. However, it is important to note that given the uncertainty in the projected change in features like the SPCZ for countries like Fiji, we currently do not have confidence in the direction of change in mean rainfall, from drier to wetter. This means that planners need to take risk-management approaches and scenario-based planning to assess adaptation actions.

Developing strategies for adaptation planning processes need to be an iterative process to take into account updated science on climate change. Adaptation decisions are not static but need to be themselves “adaptive” to new information and knowledge as it becomes available. Here, we believe our review of the main climate processes and drivers that operate in the Pacific, as well as how these processes and drivers are likely to change in the future under anthropogenic global warming, can help relevant national agencies (such as Meteorological Services and National Disaster Management Offices) clearly communicate new information to sector stakeholders and the wider community through awareness raising.

Moving forward, it is important to quantify the impacts of climate processes and drivers on extreme events in the Pacific, especially in the context of future climate under enhanced anthropogenic warming. Important information, data gaps and many uncertainties still exist in different metrics used to evaluate impacts of climate change on extreme events in the Pacific. It is anticipated that as longer temporal records of updated climate data, as well as new generations of climate models with fewer biases and deficiencies, become available in the future, our level of confidence in the adaptation planning and implementation process for Pacific Island countries will be improved.

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Data availability Available upon request from Savin Chand.

Declarations

Ethical approval Not applicable.

Consent to participate All authors give their consent to participate.

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