Chapter 6
A Review of South Pacific Tropical Cyclones: Impacts of Natural Climate Variability and Climate Change

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6.1 Introduction

Tropical cyclones are one of the costliest natural disasters impacting communities in the Pacific Island countries due to their high vulnerability and low adaptive capacity to tropical cyclone events. Strong winds coupled with heavy rainfall and coastal hazards (such as large waves and high seas) 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 as well as increasing construction and replacement costs (e.g. Kumar and Taylor 2015). For example, severe tropical cyclone Pam in 2014 caused a total economic loss of over US$449.4 million in Vanuatu (Esler 2015). This is equivalent to 64.1% of Vanuatu's annual gross domestic product. Similarly, severe tropical cyclone Winston in February 2016 crippled Fiji's economy, causing devastating damages to infrastructure and social security (Esler 2016).

Physical theory and numerical simulations suggest that human-induced global warming should increase the severity of tropical cyclones around the globe, and signals of an increasing trend of severe tropical cyclones may already be evident in the recent historical observations (e.g. Knutson et al. 2010). However, detecting anthropogenic influence on tropical cyclone trends from historical observational records, particularly for the South Pacific, is often complicated by several confounding factors. These include a lack of long-term consistent data records for trend analyses (e.g. Landsea et al. 2006; Landsea and Franklin 2013; Klotzbach and Landsea

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2015), as well as the competing influence of anthropogenic aerosol cooling (which opposes the effect of greenhouse warming, e.g. Ting et al. 2009; DelSole et al. 2011) and the presence of large natural climate variability (which masks any potential trend, e.g. Dowdy 2014).

Several efforts have been made over the recent years to improve tropical cyclone data quality for the South Pacific (e.g. Kuleshov et al. 2008, 2009; Diamond et al. 2012) and to better understand the impact of natural climate variability on tropical cyclones (e.g. Chand and Walsh 2009, 2010; Dowdy et al. 2012; Chand et al. 2013; Diamond et al. 2012, 2013, 2015). In addition, we now have 10 more years of data since the last comprehensive study on tropical cyclone trends for the South Pacific (Kuleshov et al. 2010), providing an opportunity to re-examine tropical cyclone trends using updated data records for the South Pacific basin. Advances in climate modelling—such as those from the Climate Model Intercomparison Project Phase 3 (CMIP3, Meehl et al. 2007) and Phase 5 (CMIP5, Taylor et al. 2012)—have provided another platform to examine future changes in tropical cyclone characteristics under different global warming scenarios for the Pacific Island countries (e.g. Chand et al. 2017).

A recent study by Chand (2018) has provided a review of past studies on tropical cyclones over the South Pacific basin. In this chapter, we not only review past studies on tropical cyclones but also consolidate new information derived from updated tropical cyclone data records and state-of-the-art climate model results. The first part of this chapter examines historical South Pacific tropical cyclone data and reviews the improved data records, enabling more robust research on climate variability and change. The second part looks at the impact of natural climate variability on South Pacific tropical cyclone activity. The third part emphasises the impact of climate change on tropical cyclone activity as evidenced from observational and climate modelling studies. The final part provides a summary of the review and gives recommendations for future work.

6.2 Historical Data Records and Homogeneity

The potential risks from tropical cyclone events are huge and significant. Therefore the accuracy of historical tropical cyclone records for quantitative risk assessments cannot be overemphasised, particularly for the vulnerable small island countries in the South Pacific. A number of past high-impact tropical cyclone events have been documented for the South Pacific Island countries, some extending back many hundreds of years. An archival database of historical tropical cyclone records over the period 1558–1970 contains tropical cyclone records in the form of historical notes (d'Aubert and Nunn 2012). An example is a likely cyclone near *Ontong Java* in the Solomon Islands in the year 1558:

> "Cyclone, 1558 February 1st week, Ontong Java. On the first February 1558, two ships. 'Los Reyes' (250 tons), and the 'Todos Santos' (107 tons), were sailing under the captaincy of Alvaro de Mendana. The ships narrowly avoided being shipwrecked on a reef, almost

> certainly the one near Ontong Java. Immediately after this, the vessels were swept away by a cyclone and driven south for six days. On the seventh day the weather cleared".

There are several other accounts of historical tropical cyclones in this database and elsewhere (e.g. Visher 1925; Kerr 1976; Ramage and Hori 1981; Revell and Goulter 1986). However, it should be emphasised that these accounts are scattered and incomplete as they date back to the pre-satellite era (i.e. before the 1970s) when the comprehensive monitoring of tropical cyclones, particularly over the open oceans, was not possible. Although efforts have been made in the past to create enhanced records of pre-satellite historical tropical cyclones for the South Pacific (e.g. Diamond et al. 2012), homogeneity issues still remain. Therefore, it has been recommended that South Pacific tropical cyclone datasets prior to the satellite era should be used with due diligence for climate variability and change analyses (e.g. Buckley et al. 2003).

Comprehensive compilation of observational tropical cyclone records for the South Pacific began after the 1970s when state-of-the-art satellite technologies became operational on a routine basis in this region. Estimates of tropical cyclone intensities improved after the 1980s when objective tools and methods (such as the Dvorak scheme) were established (e.g. Harper et al. 2008). These technological and methodological improvements have paved the way for several scientific investigations that advanced various areas of tropical cyclone research. Areas that are of particular significance, and therefore form basis of this review, include studies on climatological characteristics of tropical cyclones and the impact of natural climate variability and climate change on tropical cyclone activity.

In the next section, we examine climatological characteristics of tropical cyclones in the South Pacific basin (defined as the region between 0–25°S and 145°E-120°W), with particular emphasis on genesis locations, frequency, tracks and intensity. Tropical cyclone data used in this work is from the Southwest Pacific Enhanced Archive for Tropical Cyclones (SPEArTC, Diamond et al. 2012) database. Systems that reached at least the gale strength classification are considered in the analysis. This classification scheme (Table 6.1), which uses the maximum 10-min sustained wind speed, is the same as one proposed by Revell (1981) and adopted by Holland (1984), Thompson et al. (1992), Sinclair (2002) and Chand and Walsh (2010) for tropical cyclone studies in the South Pacific basin. It varies slightly from the Saffir-Simpson scale or the one used by the Australian Bureau of Meteorology. As a result, some descriptive statistics of tropical cyclone climatology may differ from those of other studies that may have included weaker storms.

Table 6.1 Tropical cyclone classification in the South Pacific basin

Intensity class	Description	Speed range (m s^{-1})
1	Tropical depression	<17
2	Gale	17–24
3	Storm	25–32
4	Hurricane	>32

Speed range is defined using 10-min sustained wind speed

6.3 Climatological Characteristics

Every year roughly 80 tropical cyclones form globally, with about one-third of them occurring in the Southern Hemisphere. In the South Pacific basin (east of 145°E), tropical cyclones can form as far east as French Polynesia (Fig. 6.1a) with an annual average of about nine tropical cyclones forming between the seasons 1981/1982 and 2016/2017. Of these, about four cyclones per year reach the severe intensity category (i.e. those that attained hurricane strength as per Table 6.1). However, the annual numbers for individual seasons can vary substantially, for example, from as low as four in 1994/1995 to as high as 16 in 1997/1998 season (Fig. 6.1b).

Tropical cyclones in the South Pacific Ocean basin mainly occur between the months of November and April, which defines a typical cyclone season with the peak activity (~ 70% of annual numbers) occurring during January–March (Fig. 6.1c). However, there are cases when tropical cyclones develop on either side of this period, including as early as October and as late as June. These cases are often tied to early onset and late decay of the El Niño-Southern Oscillation phenomenon (e.g. Chand and Walsh 2010), which is a major driver of tropical cyclone variability in the South Pacific at interannual timescale.

Tropical cyclone motion in the South Pacific basin can have different characteristics to those in other basins of the world. Here most tropical cyclones have an eastward component of motion during their lifetime or quickly recurve to the east

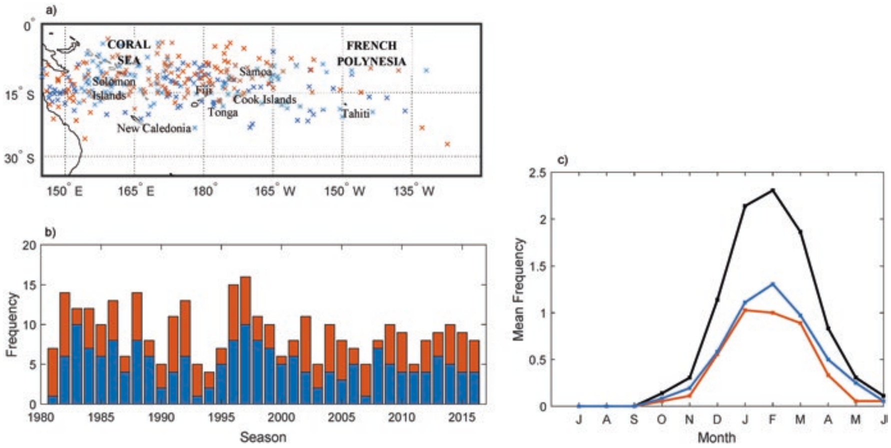

Fig. 6.1 (**a**) Tropical cyclone genesis locations in the South Pacific Ocean basin, defined as east of 145°E, (**b**) tropical cyclone counts over the period 1981–2016 and (**c**) tropical cyclone seasonality. Blue and orange indicate non-severe and severe tropical cyclones, respectively, and black line in (**c**) represents their total. Note non-severe tropical cyclones correspond to categories 1 and 2, whereas severe cyclones correspond to categories 3–5 according to the Australian intensity classification scheme. Because the Southern Hemisphere tropical cyclone season spans two calendar years (i.e. November and December of the first year and January to April of the second year), the first of the years is used in to refer to a particular season

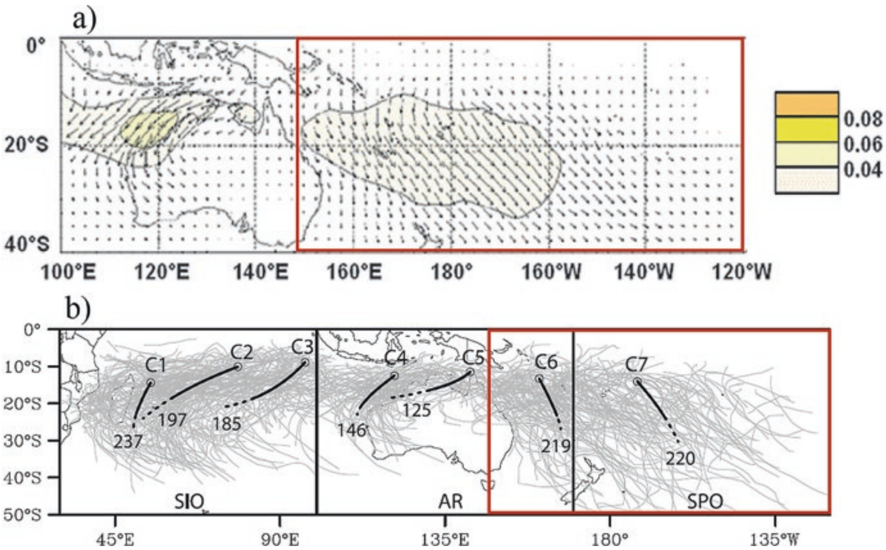

Fig. 6.2 (**a**) Annual average tropical cyclone transport fields measured in degrees per day (Source: Dowdy et al. 2012, used with permission from the American Meteorological Society) and (**b**) mean tropical cyclone track clusters (Source: Ramsay et al. 2012). The South Pacific Ocean basin is indicated by red boxes

after initially moving west (Fig. 6.2a, Dowdy et al. 2012), while the mean trajectories of tropical cyclones in other basins are generally westward. Overall, there are two main eastward moving track regimes identified in the South Pacific basin, each with their characteristic geographical domain: one is located west of the dateline and includes the Coral Sea region and the other east of the dateline (Fig. 6.2b, Ramsay et al. 2012). In a more localised study over the Fiji islands, Chand and Walsh (2009) found another track regime where westward motion exists initially in a small region west of the dateline and equatorward of 10°S before recurving eastward.

Moreover, a prominent climatic feature in the South Pacific is the South Pacific Convergence Zone (SPCZ; see Chap. 3 for details) where tropical cyclones are frequently spawned. The SPCZ is characterised by a band of high cloudiness, strong convective precipitation and low-level convergence extending from the West Pacific warm pool southeastward towards French Polynesia. It has been shown that variability of the SPCZ at different timescales, and thus the variability of tropical cyclone activity in the South Pacific, is primarily modulated by natural drivers such as the Madden-Julian Oscillation (MJO, e.g. Chand and Walsh 2010; Diamond and Renwick 2015) and the El Niño-Southern Oscillation (ENSO, Chand and Walsh 2009; Dowdy et al. 2012; Vincent et al. 2011; Jourdain et al. 2011).

In the next section, we discuss how the MJO and ENSO modulate tropical cyclone activity in the South Pacific. We limit our discussion to these modes as they are well resolved in the existing tropical cyclone data records. Other modes of variability (e.g. Interdecadal Pacific Oscillation) require longer time series of data to deduce any meaningful conclusion regarding their impacts on the South Pacific tropical cyclones, and so are not discussed hereafter.

6.4 Tropical Cyclones and Natural Climate Variability

6.4.1 Impact of ENSO

The ENSO phenomenon is a dominant mode of natural climate variability that operates at interannual timescales (see Chap. 3 for details). The term “El Niño” is commonly used to refer to the occurrence of anomalously high sea surface temperature (SST) in the central and eastern equatorial Pacific Ocean every few years (Trenberth 1997). The opposite “La Niña” phase consists of basin-wide cooling of the tropical Pacific. This anomalous warming and cooling of the central and eastern equatorial Pacific SST is coupled with the atmospheric phenomenon called the Southern Oscillation, which is characterised by a seesaw in tropical sea-level pressure (SLP) between the Western and Eastern Hemispheres. During El Niño events, the SLP falls (rises) in the central and eastern Pacific (western Pacific); the reverse occurs during La Niña events. The term “neutral phase” describes conditions when SST and SLP are near climatological averages. The zonal atmospheric circulation that arises as a result of SST and SLP coupling is called the “Walker circulation” (Walker 1923, 1924).

Initially some contradictory views existed on the relationship between ENSO and tropical cyclone activity in the South Pacific basin, primarily due to data homogeneity issues in those earlier studies. For example, Ramage and Hori (1981) and Hastings (1990) could not detect any significant relationship between tropical cyclone numbers and ENSO in the entire South Pacific basin. However, when Basher and Zheng (1995) explored the link between the Southern Oscillation Index (SOI; Troup 1965) and tropical cyclone incidence in various subregions of the South Pacific basin, they found that tropical cyclone incidence in the Coral Sea region and the region east of about 170°E significantly correlates with ENSO, although these two regions have opposite phases. Similarly, Kuleshov et al. (2009) found a statistically significant relationship between tropical cyclone numbers and various ENSO indices in the South Pacific basin.

A well-documented influence of ENSO on tropical cyclone activity in the South Pacific basin is the mean location of tropical cyclone genesis positions and tracks (see also a review by Chand 2018). In El Niño years, tropical cyclone activity systematically shifts northeastward 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 southwestward into the New Caledonia, Coral Sea and Australian regions with relatively low activity east of about 170°E. Ramsay et al. (2012), in their study encompassing the entire Southern Hemisphere, found that tropical cyclone tracks are significantly modulated by ENSO in the South Pacific basin. Consistent with other studies, they also documented an equatorward shift of the mean genesis locations of cyclones during El Niño and a poleward shift during La Niña, in addition to large changes in mean numbers. The regions of increase or decrease in tropical cyclone numbers for a given phase of ENSO are influenced by the shift in the SPCZ due to ENSO, with a southwestward shift in the SPCZ for La Niña conditions corresponding to more TCs forming around the far-west South Pacific, and an northeastward shift in the SPCZ for El Niño conditions corresponding to more TCs forming around the central South Pacific region (Fig. 6.3, Dowdy et al. 2012).

In a more localised study, Chand and Walsh (2009) found three track clusters that showed substantial modulation of tropical cyclone genesis locations and tracks over Fiji, Samoa and Tonga regions as a result of ENSO. During the El Niño phase, for example, they found tropical cyclones that formed poleward of 10°S and west of the dateline were frequently steered southeastward into the northern part of the Fiji islands and the Tonga regions by a predominant northwesterly mean flow regime. However, those that formed east of the dateline were usually steered north of the Samoa region. Cyclones, that on average formed in the mean northeasterly flow regime between 5–10°S and 170°E–180°, recurved west-southwest of the Fiji islands. For La Niña phase, they found that cyclones were often steered over the Fiji islands and the Tonga region with relatively little or no threat to the Samoa region. Furthermore, Sinclair (2002) and Chand and Walsh (2011) also examined the influence of ENSO on mean cyclone intensity in the South Pacific basin and concluded that cyclone intensity decreased rapidly around 20°–25°S latitudes during El Niño years but was often maintained as far as 40°S into the Tasman Sea in La Niña years.

A number of studies (e.g. Trenberth and Stepaniak 2001; Ashok et al. 2007; Kug et al. 2009; Kao and Yu 2009) have also identified a "non-traditional" type of El Niño event (hereafter referred to as the "El Niño Modoki" as in Ashok et al. 2007) with the above-normal SSTs confined more to the central Pacific region flanked by below-normal SSTs on the eastern and western sides. Over recent years, investigations relating to the impact of El Niño Modoki on tropical cyclones have also garnered attention in several tropical cyclone basins around the globe (e.g. Kim et al. 2009, 2011; Chen and Tam 2010; Chen 2011; Hong et al. 2011). For the South Pacific basin, Chand et al. (2013) identified four separate ENSO regimes with distinct impact on tropical cyclone genesis location and frequency. Two of the regimes were associated with traditional El Niño and La Niña events, while the other two regimes, which they termed "positive-neutral" and "negative-neutral", showed Modoki-type patterns. All of these ENSO regimes have a large impact on tropical cyclone genesis over the central southwest Pacific, with enhanced tropical cyclone activity during El Niño and positive-neutral years and reduced tropical cyclone activity during La Nina and negative-neutral years (Fig. 6.4).

Furthermore, a separate study by Diamond and Renwick (2015) looked at the impacts of the Southern Annular Mode (SAM) on climatological characteristics of the South Pacific tropical cyclones during different phases of ENSO. They found

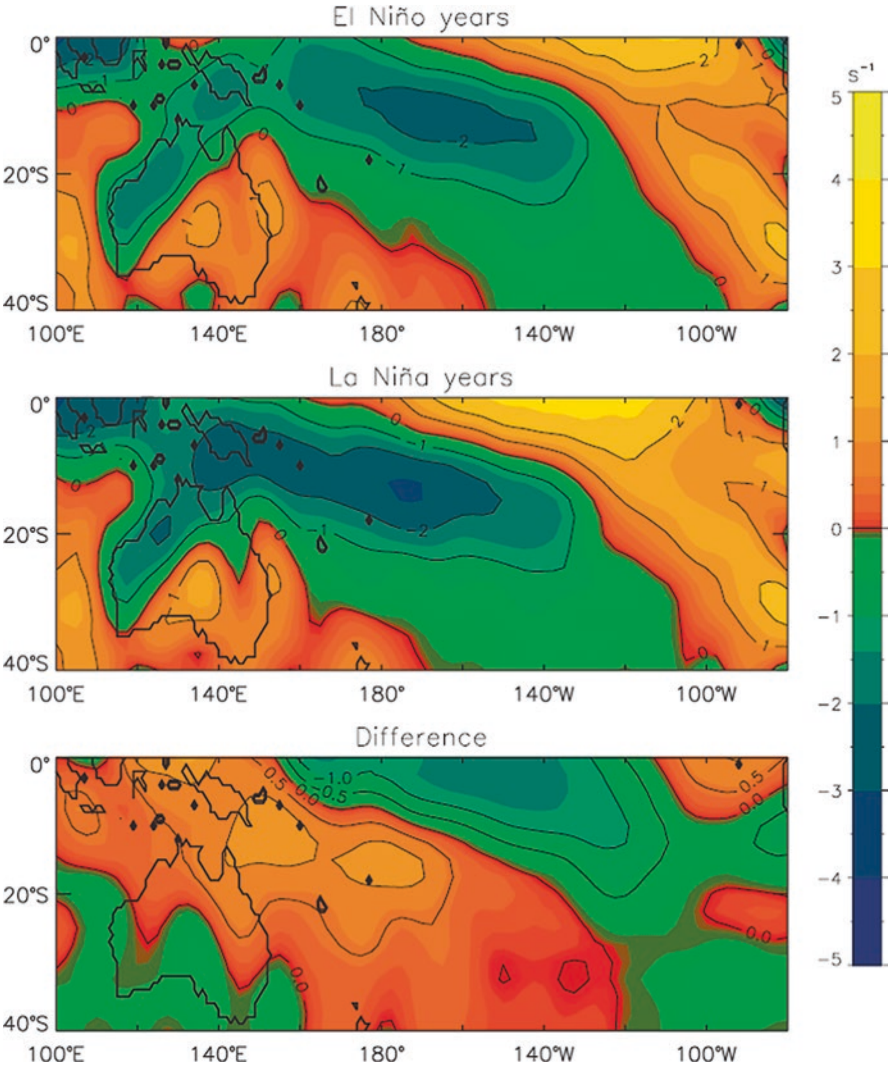

Fig. 6.3 November–January divergence of the horizontal mean wind field at 850 hPa for (top) El Niño years, (middle) La Niña years and (bottom) the difference between El Niño and La Niña years. (Source: Dowdy et al. 2012, used with permission from the American Meteorological Society)

that a synergetic relationship between the positive phase of SAM (i.e. when the belt of westerly winds contracts towards Antarctica and anomalously higher pressure dominates southern Australia) and La Niña events results in more cyclones reaching farther south, thus increasing the likelihood of tropical cyclones undergoing extra-tropical transition near New Zealand. While this relationship is statistically

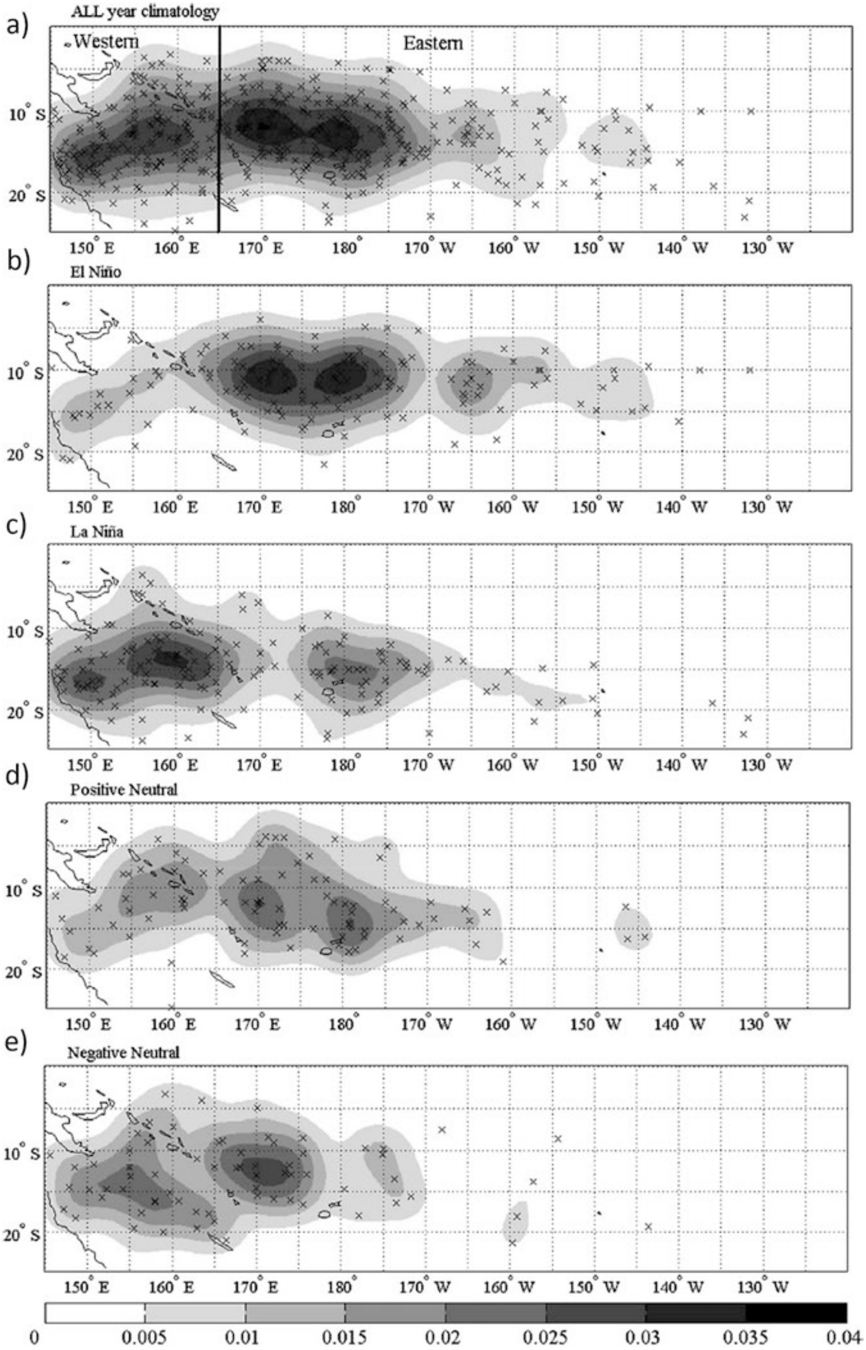

Fig. 6.4 Tropical cyclone genesis density for overall climatology and for different ENSO regimes over the period 1969/1970–2011/2012. The number of tropical cyclone genesis per year and per 2.5° × 2.5° boxes are represented as anisotropic Gaussian density distribution (shaded) and as actual genesis positions (crosses). (Source: Chand et al. 2013, used with permission from the American Meteorological Society)

significant, they found no clear mechanism that can explain this link between mid-latitude SAM and South Pacific tropical cyclones.

The relationship between ENSO and tropical cyclones in the South Pacific Ocean basin is also modulated by the MJO, which in itself is a major driver of intraseasonal variability of tropical cyclones in the South Pacific (e.g. Hall et al. 2001; Leroy and Wheeler 2008; Chand and Walsh 2010; Diamond et al. 2015) and elsewhere around the globe (e.g. Maloney and Hartmann 2000; Bessafi and Wheeler 2006 and others). In the next section, we examine how MJO modulates overall tropical cyclone activity over the South Pacific basin, as well as in interaction with different phases of ENSO given that characteristics of the MJO are linked to phases of ENSO (e.g. Hendon et al. 1999).

6.4.2 Impact of the MJO

The Madden-Julian Oscillation (MJO; Madden and Julian 1971) is characterised by an eastward propagating disturbance with a period of about 30–90 days. It is a leading mode of intraseasonal variability in the tropical atmosphere, particularly during austral summer months (see Chap. 3 for details). The propagating disturbance associated with the MJO is a centre of strong deep convection (“active phase”), flanked on both sides by regions of weak deep convection (“inactive” or “suppressed phases”).

The MJO phenomenon strongly modulates tropical cyclone activity in various cyclone basins at intraseasonal timescale (see the review by Klotzbach 2014). As the MJO progresses eastward over the equatorial South Pacific basin, it modulates large-scale environmental factors such as vertical wind shear, low-level relative vorticity and mid-level moisture that are known to affect tropical cyclone formation and intensity. When the convectively active phases of the MJO are over the South Pacific basin, tropical cyclone numbers can be significantly enhanced. In contrast, when the convectively inactive phases of the MJO are over the South Pacific basin, tropical cyclone numbers can be significantly suppressed (e.g. Fig. 6.5, Leroy and Wheeler 2008). The number of cyclones reaching hurricane intensity can also undergo significant enhancement in the active phases of the MJO when compared to the inactive phases (Chand and Walsh 2010; Klotzbach 2014).

A number of past studies have established a link between the MJO and ENSO, though the exact causative mechanism between the two is still not well understood (e.g. Hendon et al. 1999). Consequently, studies examining the relationship between tropical cyclone activity and the MJO in the different phases of ENSO have emerged for several tropical cyclone basins around the globe. For example, Chand and Walsh (2010) examined the impact of the MJO on tropical cyclones over the Fiji region, spanning the dateline. They found that if the enhanced phases of the MJO occur during El Niño events, more tropical cyclones are likely to form in the region when compared to the enhanced phases of the MJO occurring during La Niña events. Similar results were found in an earlier study by Hall et al. (2001) for the Australian

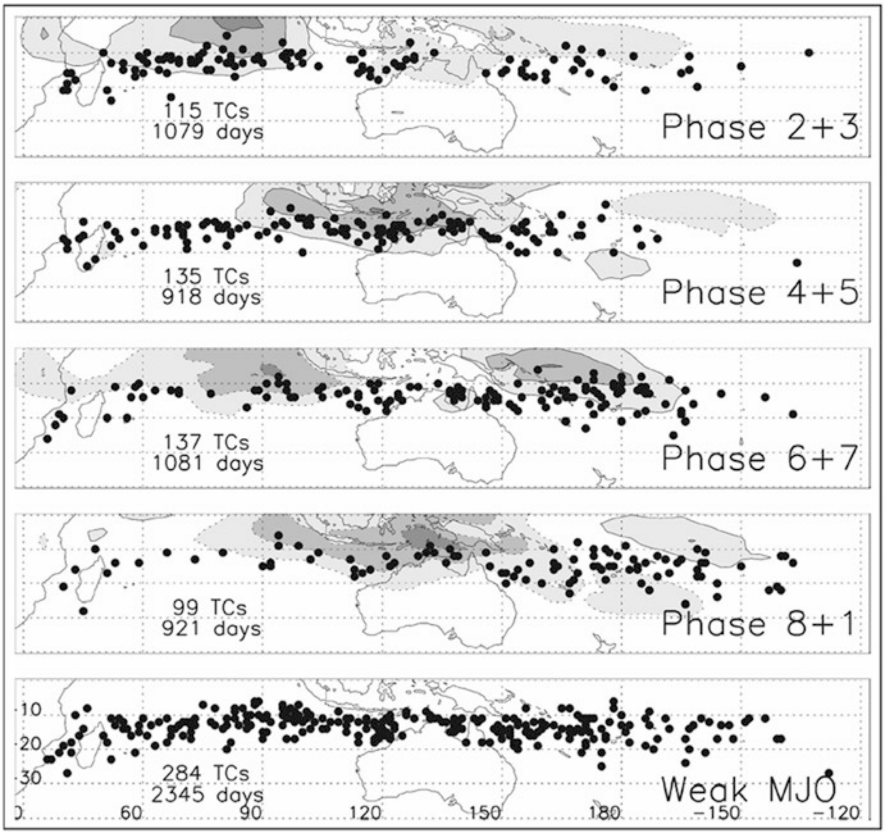

Fig. 6.5 Tropical cyclone genesis locations (dots) according to the phase of the MJO, as defined by Wheeler and Hendon (2004) over the period 1969–2004. Also shown are contours of outgoing longwave radiation (OLR) anomalies for each averaged MJO phase with negative contours solid and positive contours dashed; positive contours indicate enhanced convective activities, and negative contours indicate suppressed convective activities. Also listed are the number of tropical cyclones (TCs) counted within each phase and the number of days for which that MJO phase category occurred. (Source: Leroy and Wheeler (2008), used with permission from the American Meteorological Society)

region that showed that the relationship between the MJO and tropical cyclones is strengthened during El Niño periods.

Overall, the impacts of ENSO and the MJO are well documented for South Pacific tropical cyclones. Impacts of lower-frequency mode variability, for example, the Interdecadal Pacific Oscillation, require longer temporal records of tropical cyclones and so are not well understood for the basin. This poses a serious challenge for climate change and attribution studies as such understanding is important to deduce any meaningful information on the impact of climate change on tropical cyclone activity. Over the past decades, new tools and methods have been developed to circumvent some of these challenges in order to provide information on the impact of climate change on tropical cyclones (see the following sections).

6.5 Tropical Cyclones and Climate Change

6.5.1 Overview

There is a strong scientific consensus that anthropogenic activities are unequivocally significant contributors to global climate change (e.g. Christensen et al. 2013). There is also substantial evidence that environmental conditions that support tropical cyclones are changing as a result of anthropogenic climate change (e.g. Knutson et al. 2010; Walsh et al. 2016). However, estimating the effect of anthropogenic climate change on tropical cyclone activity can be challenging as the observed changes in the tropical cyclone activity due to anthropogenic influences are masked by the variability expected through natural causes. Additionally, systematic assessments of observed changes are further limited by insufficient long-term homogeneous data records. Whether one can develop reliable simulations of change in these environmental factors affecting tropical cyclones—and hence, changes in tropical cyclone metrics such as frequency, intensity and track distribution—is also challenging as many climate models still have biases and deficiencies in simulating these factors at local and basin scales.

Several efforts have been made over the past decade to strengthen the understanding of the links between climate change and tropical cyclones. For example, recent advances in the production of improved and more homogeneous tropical cyclone datasets (e.g. Kossin et al. 2013), as well as long-term reanalysis products (e.g. Saha et al. 2010; Compo et al. 2011), have provided some confidence in the detection and attribution of observed changes in tropical cyclone characteristics due to climate change. Increasing use of geological proxies to determine historic and prehistoric tropical cyclone variability patterns has also provided a longer climate baseline for exploring the dependence of tropical cyclone activity on climate change. Considerable effort has been made over the past few years to improve climate model performance in simulations of the climate system. This has provided opportunities to examine future projections of tropical cyclone activity, even at regional scales, in more detail than before (e.g. Chand et al. 2017).

6.5.2 Paleotempestology

In recent decades, several global studies have been undertaken to determine past tropical cyclone activity by examining evidence from historical documents and geological proxies such as oxygen isotopes in sediment cores extracted from lake beds and cave stalagmites, as well as tree-ring chronologies. Such studies, often referred to as "paleotempestology", have extended the tropical cyclone records as far back as the early Holocene (about 10,000 years ago) in many basins globally.

For example, a North Atlantic study reconstructed tropical cyclone activity over the last millennium using oxygen isotopes in deep seawater sediments (Woodruff et al. 2012). More recently, Haig et al. (2014) derived a tropical cyclone index for Australia using stalagmite records obtained from Queensland and Western Australia. They showed, on the basis of this index, that the present low levels of storm activity on the Australian coasts are unprecedented over the past 550–1500 years. Similarly, Callaghan and Power (2011) used historical documentations to show a decline in the number of severe tropical cyclone making landfall over eastern Australia since the late nineteenth century. These studies have provided scientists with a better understanding of tropical cyclone activity and natural climate variability and therefore help to determine the anthropogenic influence of climate change on tropical cyclones from natural variability.

However, research on historic and prehistoric reconstruction of tropical cyclones in the South Pacific is lacking. The focus of limited past studies in the South Pacific has primarily been on the reconstruction of general climate variability patterns and features such as El Niño Southern Oscillation, Pacific Decadal Oscillation and South Pacific Convergence Zone (e.g. Bagnato et al. 2004; LeBec et al. 2000). While ENSO is the major driver of interannual variability of tropical cyclones in the Pacific in the present climate, the extent to which it impacted tropical cyclones in the historic and prehistoric climate is not known, leaving unanswered questions on the sensitivity of tropical cyclones to ENSO before the modern era. The link between natural climate variability and tropical cyclones in the historic and prehistoric context can provide climate scientists with crucial information on tropical cyclones and climate change in the South Pacific. Particularly, site-specific geological proxies can form important indicators of extreme landfalling tropical cyclone impacts on individual island countries as they often preserve high-resolution time series information of extreme events.

6.5.3 Trends from Observations

A previous review (Knutson et al. 2010) concluded that there was no significant change in the total number of cyclones over the period 1970–2004 both globally and for individual basins with the exception of the North Atlantic. However, a substantial increase in the global number of the most intense tropical cyclones was reported from 1975 to 2004 (Webster et al. 2005). This finding was later contested by Klotzbach and Landsea (2015) who argued that the trend was attributed to improvements in tropical cyclone observational practices at various tropical cyclone warning centres, primarily in the first two decades of that study.

For the South Pacific basin, Kuleshov et al. (2010) found no apparent trend in the total number of tropical cyclones over the period 1981–2007, nor any significant

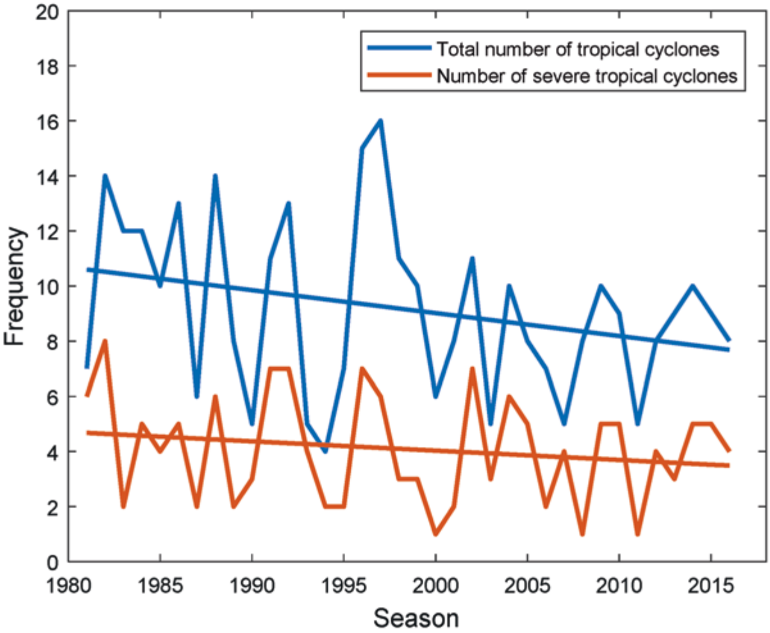

Fig. 6.6 Frequency and associated trends for the total number of tropical cyclones (blue) and severe tropical cyclones (orange) in the South Pacific over the period 1981/1982 to 2016/2017

trend in the number of severe tropical cyclones (i.e. cyclones with central pressure below 970 hPa). We have repeated the trend analysis for the South Pacific basin with 10 years of additional data from the SPEArTC dataset (Diamond et al. 2012), taking into consideration influences of various modes of natural variability (Fig. 6.6). Consistent with the earlier work of Kuleshov et al. (2010), we also found a weak and statistically insignificant trend both in the total number of cyclones and in the frequency of severe tropical cyclones. It is important to emphasise here that lack of trends in the observed record over the period 1981–2016 does not negate the presence of trend. As more data becomes available in the future to better quantify low-frequency variability, such as Interdecadal Pacific Oscillation (IPO), more confidence can be expected in the analyses of tropical cyclone trends and climate change.

Regardless, while temporal homogeneity of tropical cyclone data is of concern, studies are now emerging on metrics that are not very sensitive to past data records. For example, Kossin et al. (2014) examined the average latitude when tropical cyclones reach their lifetime maximum intensity (LMI) over the period 1982–2009. They found a pronounced trend in poleward migration of tropical cyclone LMI in both the Northern and the Southern Hemispheres. However, this was contradicted by Moon et al. (2015) who argued that poleward migration of the LMI is basin-dependent and can be greatly influenced by multi-decadal variability, particularly for the Northern Hemisphere basins. For the Southern Hemisphere basins, both studies agree on a significant poleward migration of the LMI, which could be a result of a poleward expansion of the tropics due to anthropogenic climate change as suggested by theoretical (Held and Hou 1980) and modelling (Lu et al. 2007) studies. This may imply that tropical cyclone exposure is likely to increase in the future climate for the small island countries that are located farther south of the equator in the South Pacific basin. However, more research is needed to determine and quantify the extent of the exposure.

6.5.4 Results from Climate Modelling Experiments

In the absence of homogeneous observed records for robust conclusions on tropical cyclones and climate change, analytical tools such as Global Climate Models (GCMs) are used to understand how climate variability and change may impact tropical cyclones in various regions around the globe. Over the past several years, considerable effort has been made to improve climate model performance in the simulation of various aspects of the climate system including tropical cyclones. Methods of detecting tropical cyclones in climate model simulations have also improved substantially (e.g. Tory et al. 2013a). However, some caveats still remain in resolving certain aspects of tropical cyclones, particularly intensity due to coarse horizontal resolutions that can vary from about ~100–300 km for CMIP3 and CMIP5 models to ~10–50 km for new generation of high-resolution models. Several downscaling strategies (e.g. Emanuel et al. 2008) and theoretical approaches (e.g. Emanuel 1987; Holland 1997) have been applied to mitigate coarse resolution issues and, therefore, better understand the impact of climate change on tropical cyclone intensities.

A number of climate modelling studies have a consensus projection of a likely decrease in the globally averaged tropical cyclone frequency (~5–30%) by the late twenty-first century. There is also a clear tendency among the high-resolution models to project a global increase in the frequency of stronger tropical cyclones (~5–30% for Category 4 and 5 cyclones on the Saffir-Simpson scale), as well as an increase in tropical cyclone LMI (~0–5%) and tropical cyclone rainfall rate (~5–20%), by the late twenty-first century (see a review by Christensen et al. 2013). However, large variations in projected changes of tropical cyclone characteristics can occur between different climate models at a regional scale, particularly for the Northern Hemisphere basins (Fig. 6.6). This could be potentially attributed to climate model deficiencies and biases in simulating regional changes in conditions known to affect tropical cyclone variability and change.

For the South Pacific basin, a multi-model study reported a consistent decrease (~3–27%) in tropical cyclone frequency by the late twenty-first century across all models (Fig. 6.7, Tory et al. 2013b) giving more confidence in the projection results. However, there is no substantial projected change in the spatial distribution of genesis locations and tracks over the South Pacific (Fig. 6.8). Note that projected changes in TC track density between the current- (1970–2000) and the future-climate (2070–2100) simulations are constructed using the high emissions

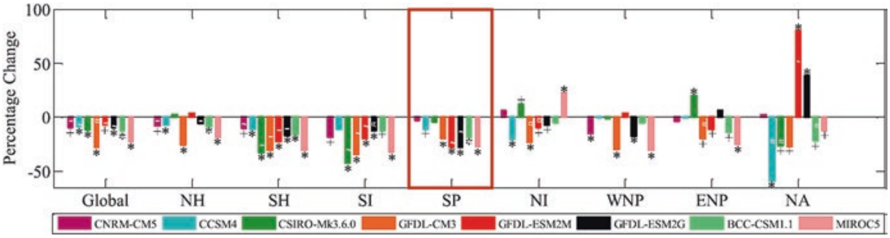

Fig. 6.7 Percentage change in the mean tropical cyclone frequency between the late twentieth (1970–2000) and late twenty-first (2070–2100) centuries for selected CMIP5 models. Changes that are significant at 95% and 90% confidence levels are indicated by asterisk and plus symbols, respectively. The South Pacific basin is highlighted in the red box. (Source: Tory et al. 2013b, used with permission from the American Meteorological Society)

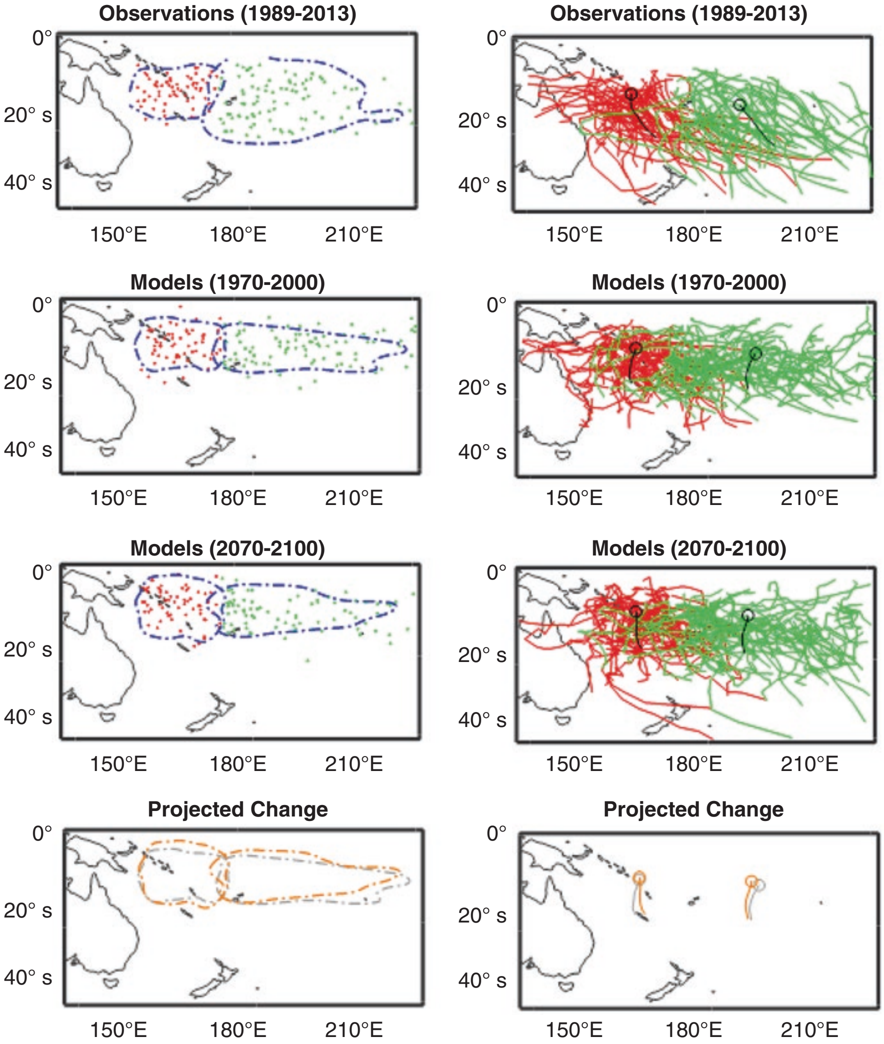

Fig. 6.8 Kernel density contours enclosing 75% of the tropical cyclone genesis locations (left panel) and mean track trajectories (right panel) for the South Pacific basin. A random sample, consistent with observational climatology, for model tropical cyclone genesis locations and tracks are selected and plotted on the figures. Projected changes of genesis locations and tracks between the late twenty-first-century (orange) and late twentieth-century (grey) simulations are also shown (bottom panel)

Representatives Concentration 8.5 Pathways (RCP8.5; e.g. Riahi et al. 2011). RCP8.5 represents an approximately 8.5 W m^{-2} increase in radiative forcing values in the year 2100 as compared to the pre-industrial emission levels and was chosen to best elucidate any changing TC behaviour in a warmer climate.

In addition, a recent study by Chand et al. (2017) used state-of-the-art climate models from the CMIP5 experiments to show robust changes in regional-scale ENSO-driven tropical cyclone variability by the end of the twenty-first century (Fig. 6.9). In particular, they showed that tropical cyclones become more frequent (~20–40%) during future-climate El Niño events compared to present-climate El Niño events—and less frequent during future-climate La Niña events—around a group of small island nations (e.g. Fiji, Vanuatu, Marshall Islands and Hawaii) in the Pacific. Their results have important implications for climate change and adaptation pathways for the vulnerable small island nations in the South Pacific. The study

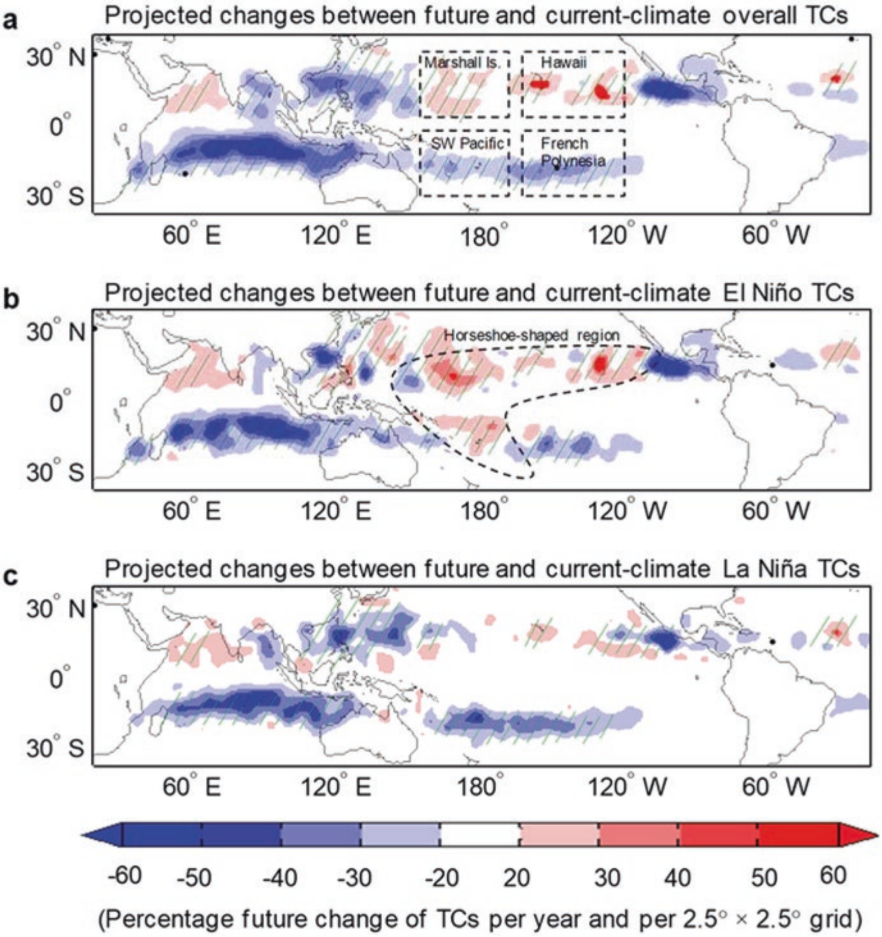

Fig. 6.9 Projected changes in tropical cyclone density between the late twentieth and late twenty-first centuries for (**a**) overall climatology, (**b**) El Niño years and (**c**), La Niña years. Red shading indicates projected increases in tropical cyclone frequency. Stippling denotes changes that are statistically significant at the 95% level. (Source: Chand et al. 2017)

shows that even though the overall frequency of tropical cyclones is likely to decrease in the future climate, large-scale drivers of climate variability (such as ENSO) are crucial in determining regional-scale changes in tropical cyclone characteristics.

6.6 Socio-economic Impacts of Tropical Cyclones

Social and economic impacts of tropical cyclones—often arising from strong winds, heavy rainfall and storm surges—can be severe in the South Pacific Island countries due their low adaptive capacity and high vulnerability. When tropical cyclones pass over an island nation, the extent of damage extends largely well beyond the coasts, affecting significant proportion of the population and infrastructure at national scale. This makes small island countries in the South Pacific one of the most exposed groups to tropical cyclones (Nurse et al. 2014). Severe tropical cyclones *Pam* over Vanuatu and *Winston* over Fiji give an insights into the extent of destructions that can be caused by tropical cyclone events over the small island countries in the South Pacific. This not only includes damages to critical infrastructure such as roads, dwellings, hospitals and environment but also loss of life and livelihood even for several weeks in the aftermath of a tropical cyclone event.

With growing threats from human-induced climate change, impacts of TCs are likely to exacerbate further in the future climate by, for example, increasing coastal flood risks through enhanced TC-induced rainfall rates (e.g. Knutson et al. 2010; Patricola and Wehner 2018), higher sea-level rise exacerbating the coastal hazards (e.g. Woodruff et al. 2013) and enhancing TC wind speed intensity (Patricola and Wehner 2018). These changes are likely to put additional pressures on the Pacific Island communities in their effort towards building adaptive capacity and climate resilience, as well as enhancing disaster risk reduction (e.g. McGray et al. 2007).

6.7 Summary

We presented a review of the impact of natural climate variability and climate change on tropical cyclone activity in the South Pacific basin. Where possible, we have also consolidated past literature with new results using updated data and climate model results. We first discussed how the impact of different modes of natural climate variability modulates South Pacific tropical cyclones, with emphasis on the Madden-Julian Oscillation (MJO) and El Niño-Southern Oscillation (ENSO) phenomena. We then presented results from the historical analyses and climate modelling studies on the extent climate change has impacted tropical cyclones in the South Pacific Island countries.

It is well-established that in the South Pacific, tropical cyclone activity systematically shifts northeastward during El Niño events, reaching as far as the Cook

Islands and French Polynesia with the greatest incidence around the dateline and the Fiji islands (e.g. Basher and Zheng 1995; Chand and Walsh 2009; Vincent et al. 2011). Simultaneously, low activity dominates the Coral Sea and Australian regions (e.g. Basher and Zheng 1995; Ramsay et al. 2012). In contrast, the reverse occurs during La Niña events when tropical cyclone activity is displaced southwestward into the Coral Sea and Australian region with relatively low activity east of the dateline. In addition to conventional El Niño and La Niña events, two other regimes are found to modulate tropical cyclones in the South Pacific: "positive-neutral" and "negative-neutral" regimes that showed ENSO Modoki-type SST patterns (Chand et al. 2013).

Similarly, the MJO phenomenon has a significant impact on intraseasonal variability of tropical cyclones in the South Pacific. For example, when the convectively active phases of the MJO are over the South Pacific basin, tropical cyclone numbers can be significantly enhanced. In contrast, the reverse occurs during convectively inactive phases of the MJO when tropical cyclone numbers are substantially suppressed (Leroy and Wheeler 2008; Chand and Walsh 2010; Klotzbach 2014).

Moreover, tropical cyclone activity in the South Pacific can be substantially influenced by global warming. While no significant attributable trend has yet appeared in the observed number of tropical cyclones over the last few decades due to insufficient data records, climate modelling studies show significant changes in the overall frequency of tropical cyclones in the South Pacific basin in future (e.g. Tory et al. 2013b; Chand et al. 2017). Overall, tropical cyclones are projected to become less frequent but potentially more intense, by the late twenty-firs-century compared to late twentieth-century climatology (e.g. Knutson et al. 2010). A recent study by Chand et al. (2017) showed that tropical cyclones become more frequent (~20–40%) during future-climate El Niño events compared to present-climate El Niño events—and less frequent during future-climate La Niña events—around a group of small island countries (e.g. Fiji, Vanuatu, Marshall Islands and Hawaii) in the Pacific.

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 South Pacific tropical cyclones. Rising sea levels due to global warming will also increase many of the coastal impacts of tropical cyclones in small islands (e.g. Nurse et al. 2014). However, much further work is required on this theme in small island situations, especially comparative research. Important information, data gaps and many uncertainties still exist on impacts of tropical cyclones in small islands. This research will be feasible when longer temporal records of updated tropical cyclone data, as well as new generations of climate models with fewer biases and deficiencies, become available in the future. Such information would raise the level of confidence in the adaptation planning and implementation process in small islands in the South Pacific.

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