Characteristics of Tropical Cyclones in the Southwest Pacific

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Abstract

Geographic and meteorological characteristics of 479 tropical cyclones (TCs) in a study domain in the Southwest Pacific (defined by 135°E–120°W and 5–65°S) over the past 48 TC seasons, from 1969–1970 to 2016–2017, were examined using the latest Southwest Pacific Enhanced Archive of TCs dataset. Examined metrics include the TCs' geographic distributions, numbers, intensities, length in days (TC days), accumulated cyclone energy (ACE), and power dissipation index (PDI). The results show increasing TC activities in the western, northwestern, northern, and central subdomains of the nine subdomains in the study domain. The average latitudes of TC genesis and maximum intensity remained almost unchanged. Most TCs took southward to southeastward paths, and most attained their maximum intensities in the western and central parts of the study domain. The annual number of TCs and TC days decreased over the study period, while the numbers of stronger TCs slightly increased, and stronger TC days increased. The highest annual lifetime-maximum intensity and average annual lifetime-maximum intensity also increased. The highest annual maximum intensification rates did not change much over the study period, nor did ACE and PDI. The results show correlations between the highest annual lifetime-maximum intensity and average sea surface temperature (SST) variations, as well as correlations between TC days and average SST variations in the region.

Keywords tropical cyclones; Southwest Pacific; sea surface temperature; interannual variability; long-term trends

The World Bank has reported that TCs are the most dangerous form of natural disaster in the Southwest Pacific in terms of economic loss (World Bank 2013). The region’s greatest catastrophes include the severe Category (Cat) 5 Cyclone Yasi that affected the State of Queensland, Australia, in 2011, causing over $15 billion U.S. dollars (USD) of damage and losses (World Bank 2011), Cyclone Pam (Cat 5) that affected the Vanuatu islands in 2015 with an estimated loss of $449.9 million USD (Government of Vanuatu 2015), and Cyclone Winston (Cat 5) that devastated the Fiji islands in 2016 with an estimated loss of $0.9 billion USD (Government of Fiji 2016). Previous severe disaster records, along with projections that global TC intensity will rise in connection with global warming (e.g., Gualdi et al. 2008; Zhao et al. 2009; Murakami and Sugi 2010; Knutson et al. 2010), indicate elevated future risk for the region. Comprehensive studies of TCs are essential for understanding how these storms behave in the region.

Earlier studies of TCs in the Southwest Pacific include the work of Chand and Walsh (2009), who used Joint Typhoon Warning Center (JTWC) best-track data from 1970 to 2006 to investigate the interannual variability of TC locations in the Fiji–Samoa–Tonga region, an area bounded by 5°S, 25°S, 170°E and 170°W (Fig. 1). They found that TC genesis locations and tracks appeared to be strongly influenced by the El Niño–Southern Oscillation (ENSO) and were strongly correlated with associated large-scale environmental influences (850 hPa cyclonic vorticity, 200 hPa atmospheric divergence, and environmental vertical wind shear). Chand and Walsh (2011) extended this work by analyzing the temporal and spatial variation of accumulated cyclone energy (ACE) over the Fiji–Samoa–Tonga region. They concluded that the most favorable region for large ACE values is north of 15°S, particularly during the warmer (El Niño) phase of ENSO, when TC length (in days) and mean intensity are the main controlling factors of ACE. Recent work by Iizuka and Matsuura (2012) showed that, the frequency of TCs in the northeastern quadrant of the Southwest Pacific increases during the El Niño and decreases during the cooler (La Niña) phase of ENSO. Using satellite data and European Medium-Range Weather Forecast (ECMWF) Re-analysis (ERA-40) over the 1979–2001 period, Vincent et al. (2009) found the interannual variability of the South Pacific Convergence Zone (SPCZ), which is strongly linked to ENSO, may have a significant influence on TC genesis in the South Pacific (0°S, 30°S, 140°E, and 120°W). These four studies highlighted ENSO’s influence on temporal and spatial variations of parameters associated with TCs.

The study of Basher and Zheng (1995) in the South Pacific (area bounded by 10°S, 22°S, 150°W and 130°W; Fig. 1) used TC information for 1969–1989 from the New Zealand Meteorological Service. They concluded the sea surface temperature (SST) and Southern Oscillation (SO) phase mainly contribute to TC numbers’ spatial variation. Dare and Davidson (2004), using 40 years of satellite observations to examine TC characteristics in the Australia region, identified areas of TC genesis in the Gulf of Carpentaria (Gulf in Fig. 1) and near the coastline around 145–155°E. Dowdy et al. (2012) used the Southern Hemisphere TC achieve compiled at the National Climate Center of the Australian Bureau of Meteorology to study TCs’ climatology over the South Pacific Ocean (dashed rectangle in Fig. 1) from 1969 to 2010. They found that TC activity is broadly consistent with large-scale environmental parameters (SST, vertical wind shear, vorticity, and relative humidity). For example, they found that TC genesis is confined to around 5–20°S, with a northeastward shift during El Niño and a southwestward shift during La Niña.

Ramsay et al. (2014) reported a decrease in the number of TCs during the 1977–2011 period in the Coral Sea Basin (yellow rectangle in Fig. 1). Webster et al. (2005) examined the number of TCs and the number of cyclone days over the combined South Pacific Ocean (green rectangle in Fig.1) and the South Indian Ocean (5°S, 20°S, 50°E and 115°E) for the 1970–2004 period and concluded that none of the trends was statistically different from zero. Kuleshov et al. (2010) concluded there were no apparent trends in the annual number of TCs or stronger TCs during the 1969–1970 and 2006–2007 periods over the South Pacific Ocean (SPAC, same domain as Webster et al. 2005).

Previous studies have differed widely in their choice of datasets, methodology, and study area. Moreover, earlier studies were hampered by spatiotemporal inconsistencies in observations and unreliable datasets. Apparently in the Southwest Pacific, documenting TC characteristics is a greater challenge than in most other ocean basins. The recently produced South Pacific Enhanced Archive of Tropical Cyclones (SPEArTC) dataset, described by Diamond et al. (2012), is a reliable platform for research on TCs in the region. It includes TC tracks from the International Best Tracks for Stewardship (IBTrACS) dataset, plus newly discovered information from the Pacific Island Meteorological Services (Fiji, New Caledonia, New Zealand,
Tonga, Solomon Islands and Vanuatu) that is not included in other best-track datasets. SPEArTC also incorporates much previous work on TC climatology in the Southwest Pacific region (Diamond et al. 2013; Ramsay et al. 2014). Even though there are still uncertainties in best-track datasets (Torn and Snyder 2012; Hodges et al. 2017), the use of SPEArTC, particularly for TC-related studies in the Southwest Pacific region, is now widespread (e.g., Diamond et al. 2013; Magee et al. 2016; Blunden and Arndt 2016, 2017).

The present study aimed to provide a broad assessment of recent TC activity trends in the Southwest Pacific by considering a variety of metrics, such as the geographical distribution (origins and tracks), numbers, intensities, lengths (in days), ACE, and the power dissipation index (PDI). The analyses were limited to trend detection, with no detailed investigation of the mechanisms leading to such variability. We evaluated how these TC metrics varied over the 48 most recent TC seasons and their possible connection with SST, a topic of controversy for many years. Our goal was to offer clear guidance that might enhance the capabilities of individuals, societies, and communities to anticipate and ultimately mitigate future TC risks.

2. Data and methodology

2.1 TC best-track data

Best-track data used in this study were obtained from the SPEArTC dataset, which contains information for all TCs originating in the Southwest Pacific, encompassing the region defined by 135°E, 120°W, 5°S, and 65°S, from 1840 to the present. Because SPEArTC incorporates data from multiple sources, the developers used a quality control procedure to inspect and identify duplicate tracks; therefore, in the present study, the data is used as provided. For full details of the SPEArTC dataset, readers can refer to Diamond et al. (2012) and Magee et al. (2016). At the time of this study, SPEArTC had been extended to the latest TC season (i.e., 2016–2017). Note that the official TC season in the Southwest Pacific is typically from October to April, and TC seasons hereafter are named with the latter year; for example, the TC season starting in October 2010 and ending in April 2011 is referred to as the 2011 TC year.

We examined TCs from TC years 1970 to 2017, representing the era of satellite observations, when TC temporal and spatial information appeared more reliable (Webster et al. 2005; Diamond et al. 2012, 2013), and to avoid any substantial uncertainty because of data deficiencies during the pre-satellite era. For instance, Hassim and Walsh (2008) explained that, since 1970, there has been a steady increase in satellite coverage (spatial, spectral, and temporal resolution) over the Australian region (90°E, 160°E, 5°S, and 30°S). Terry and Gienko (2010) stated that, since the 1960s, satellite observations have led to more accurate and reliable TC observations in the South Pacific (160°E, 120°W, 0°, and 25°S). The present TC dataset provides information (typically at 6 h intervals) on latitude and longitude of cyclone centers, maximum (10-min average) sustained near-surface wind speed \( V \), and minimum central sea level pressure.

We chose \( V \) over sea level pressure to conduct our analyses because the dataset is more complete for \( V \) and for consistency with most previous studies. Moreover, wind speed is more directly related to potential TC impact than sea level pressure. Because \( V \) is not determined for some time intervals in the dataset, data from those times were not used in any analysis that depends on \( V \), but the corresponding location information was still used for spatial analyses of all storms, including non-TC storm periods. In accordance with the World Meteorological Organization (WMO)'s definition of TCs in the South Pacific and Southeast Indian Ocean (World Meteorological Organization 2016), only storms with \( V \) greater than or equal to 34 knots were considered TCs in this study. The present study domain (bounded by 135°E, 120°W, 5°S, and 35°S, the red rectangle in Fig. 1) slightly differs from the official WMO definition of the Southwest Pacific (160°E, 120°W, 0°, and 50°S). We extended the domain westward to include TCs that form west of 160°E before spending most of their lifetimes in the official WMO domain (Diamond et al. 2012), and we chose 35°S as the southern limit to remove any extratropical influences.

2.2 Geographic distribution of TCs

When investigating TCs’ decadal and spatial distributions over the most recent 48 years, we were interested in identifying (1) TC locations, (2) where TCs reach their peak intensities, and (3) the TCs’ paths. We also investigated the annual changes in the average latitudes of TC genesis and the average latitudes of TC lifetime-maximum intensity. We divided the study domain into nine subdomains (refer Fig. 3c), named northwest (NW), north (N), northeast (NE), west (W), central (C), east (E), southwest (SW), south (S), and southeast (SE).

In this paper, the TC genesis location is defined as the location where the intensity first reached \( V \geq 34 \) knots. The location of TC maximum intensity, \( LV_{\text{max}} \)
hereafter, is the location where the TC first attained its lifetime-maximum intensity \( (V_{\text{max}}) \) and at least 6 h after genesis.

2.3 TC numbers

The annual variation in TC numbers was evaluated for all TCs, for weak TCs, and for intense TCs. We separated the overall numbers into weak and intense TCs, using a threshold \( V \) of 86 knots, to better assess the likely damage associated with a TC. TCs with \( V \geq 86 \) knots correspond to severe Cat 4 and Cat 5 TCs in the Southwest Pacific region; such TCs are typically more disastrous. For instance, the high winds of a single intense TC may have more severe consequences than the winds of several weak TCs. A very similar threshold was used in some previous studies that we referred to in the present study (e.g., Webster et al. 2005; Hoarau et al. 2018). For simplicity, weak and intense TCs are referred to here as weaker TCs \( (V < 86 \) knots) and stronger TCs \( (V \geq 86 \) knots), respectively.

2.4 TC intensity

TC intensity is represented by \( V \), the maximum (10-min average) sustained near-surface wind speed. The lifetime-maximum intensity, \( V_{\text{max}} \), is defined as the maximum value of \( V \) during the lifetime of each TC. The highest \( V_{\text{max}} \) of all TCs in each year is expressed as \( \hat{V}_{\text{max}} \) and defined by

\[
\hat{V}_{\text{max}} = \text{Max}(V_{\text{max},i}),
\]

where \( V_{\text{max},i} \) is the lifetime-maximum intensity of individual TC/ in knots.

The average maximum intensity of all TCs in each TC season referred to hereafter as \( \bar{V}_{\text{max}} \) and is defined by

\[
\bar{V}_{\text{max}} = \frac{\sum_{i=1}^{N} V_{\text{max},i}}{N},
\]

where \( N \) is the number of TCs in each TC season.

We also evaluated the annual variation in the maximum intensification rate \( (IR_{\text{max}}) \) of TCs. The intensification rate at a given time is defined as the increase in \( V_{\text{max}} \) over a 6 h period. The speed at which a TC intensifies often leads to large forecast errors, especially when a sudden change occurs (Rappaport et al. 2009). Very large intensification rates can be problematic, and even disastrous, if people are unaware of these dramatic increases in strength. Here \( IR_{\text{max}} \) is the lifetime-maximum rate of change in the intensity of a particular TC and is defined by

\[
IR_{\text{max}} = \text{Max} \left( \frac{\Delta V}{\Delta t} \right) = \text{Max} \left( \frac{V_n - V_{n-1}}{t_n - t_{n-1}} \right),
\]

where \( t \) is the observation time and \( n \) is an index of time. The highest \( IR_{\text{max}} \) in each year, \( \text{\hat{I}}R_{\text{max}} \), is defined by

![Fig. 1. Map of the Southwest Pacific showing domains of the present study (Study Domain, red outline) and previous studies: Basher and Zheng (1995) in purple (SP), Chand and Walsh (2009, 2011, 2012) in blue (FST), Webster et al. (2005) and Kuleshov et al. (2010) in green (SPAC), Dare and Davidson (2004) in brown (N & E Australia), Dowdy et al. (2012) in gray (SPO), Ramsay et al. (2014) in yellow (Coral Sea). Gulf of Carpentaria (Gulf) is a large bay located in the north of Australia. See the text for study descriptions.](image-url)
by
\[
\widehat{IR}_{\text{max}} = \text{Max} (IR_{\text{max},i}),
\]
where \( IR_{\text{max},i} \) is the lifetime-maximum intensification rate of individual TC \( i \) in knots per hour.

### 2.5 TC days

TC days can give a good idea of the threat duration and hence the possibility of severe impacts. We adopted the definition of “TC Days” from Frank and Young (2007) and Webster et al. (2005), which is the total number of days that a storm sustains TC intensity. The annual number of TC days is the sum of all TC days within each season,

\[
\text{TC days} = \frac{1}{24} \sum_{i=1}^{N} \sum_{n=2}^{M_i} (t_{i,n} - t_{i,n-1}),
\]

where \( t_{i,n} - t_{i,n-1} \) is the time difference of two observations in hours, \( M_i \) is the number of observations in each TC, and the summation is divided by 24 to convert from hours to days.

### 2.6 Accumulated cyclone energy

The quantity ACE is proportional to a TC’s kinetic energy and has been used in previous studies to measure TC activity (e.g., Camargo and Sobel 2005; Chand and Walsh 2011; Villarini and Vecchi 2013; Corporal-Lodango et al. 2016; Zhang et al. 2016). As in previous studies, ACE in this study is calculated by summing the square of \( V \) for each 6 h interval (usually measured at 0000, 0600, 1200, and 1800 UTC), integrated over each TC’s lifetime. Annual ACE values are obtained as an annual accumulation from

\[
\text{ACE} = \sum_{i=1}^{N} \sum_{n=1}^{M_i} V_{i,n}^2,
\]

where \( V_{i,n} \) in m s\(^{-1}\) is defined every 6 h for each TC. The unit of the ACE is m\(^2\) s\(^{-2}\) which is equivalent to J kg\(^{-1}\) and the latter is used in this paper.

### 2.7 Power dissipation index

The PDI has been used in previous studies to assess the associated power and destructiveness of TCs in different regions (Emanuel 2007; Murakami et al. 2014; Li et al. 2017). Based on the cube of \( V \) at each time interval (Emanuel 2005), the annual PDI is defined by

\[
PDI = \sum_{i=1}^{N} \sum_{n=1}^{M_i} V_{i,n}^3.
\]

Note that we converted the units of \( V \) from knots to m s\(^{-1}\) (1 knot \( \approx 0.51 \) m s\(^{-1}\)) only for our calculations of the integrated TC intensity metrics such as ACE and PDI.

### 2.8 Sea surface temperature dataset

Since SST is a key thermal potential required for TC formation and fueling (Gray 1968), we analyzed SST’s long-term seasonal variability, averaged over the months of the TC season, and conducted a correlation analysis to describe TCs’ variability. The SST data were obtained from the Extended Reconstructed Sea Surface Temperature archive, version 5 (ERSSTv5), a global monthly dataset from the U.S. National Oceanic and Atmospheric Administration, with a horizontal resolution of \( 2^\circ \times 2^\circ \) (Huang et al. 2017). The SST anomalies were computed with respect to the 1971–2000 climatology as a baseline to depict change.

### 2.9 Trends and correlation analyses

Linear regression lines were fitted to the time series of the TC metrics, explained in sub Section 2.3 and defined by Eqs. (1)–(7), and to the SST time series (Fig. 12) to describe their long-term trends. We also used correlation analysis as an explanatory tool to quantify the relative strengths or linear relationships between variables. In this paper, the strength of such relationships is based on the coefficient of determination \( (r^2) \) and characterized as very strong \( (r^2 = 0.8–1.0) \), strong \( (0.6–0.79) \), moderate \( (0.4–0.59) \), weak \( (0.2–0.39) \), or very weak \( (0–0.19) \).

### 3. Results

#### 3.1 TC geographical distribution

The Southwest Pacific is generally recognized as a genesis region for TCs, which usually originate nearer the equator, where the necessary conditions for TC genesis are most favorable. In the southern hemisphere, the meridional component of TCs’ motion is typically southward. In this study, it was evident that some TCs entered the mid-latitudes during the study period and tracked further south, with a few going beyond 50°S (Fig. 2a). A number of TCs moved west and made landfall on the eastern Australian coast. Some Southwest Pacific TCs, especially those generated in the Gulf of Carpentaria (Fig. 1), traveled west, to the western part of Australia and beyond into the Southern Indian Ocean. In the study domain, the
The number of tracks per decade for storms of all intensities, including non-TC storms, is basically decreasing (Fig. 2). The 2000–2009 decade have the smallest number of tracks (105 tracks of all intensities). The locations of TC genesis in the Southwest Pacific are predominantly in the N, NW, and W subdomains; the combined total of 358 TCs accounts for 74.7% of the total number (Fig. 3). A total of 51 TCs were generated west of 143°E in the Gulf of Carpentaria, which is a high concentration in a small ocean area. A notable number of TCs were also generated off northeastern Australia and around the Vanuatu islands. The C subdomain, near Fiji, and the W subdomain, from near New Caledonia to the east coast of Australia, had the most LV_{max} locations, which together make up 65.7% of the total number (Fig. 3c). As expected, LV_{max} locations tend to lie south to southeast of the genesis locations. Four TCs in the dataset (storm 14...
of 1979, storm 7 of 1982, storm 7 of 1986 and storm 6 of 2003) only reached TC intensity during one time interval and, thus, did not have a lifetime-maximum intensity according to our definition (Section 2.2).

Figure 4 shows a time series of the annual average latitudes of TC genesis and $V_{\text{max}}$. For this calculation, we excluded 89 TCs that formed west of 155°E in the Gulf of Carpentaria and along the northeast coast of Australia because their movements were very probably restricted by the presence of dry land. The annual average TC genesis latitude (Fig. 4a) had a trend of 0.603 km yr$^{-1}$ away from the equator, and the average $V_{\text{max}}$ latitude (Fig. 4b) had a trend of 0.11 km yr$^{-1}$ away from the equator and both trends are considered small. TC genesis latitudes had a range of 1400–2200 km from the equator, whereas $V_{\text{max}}$ latitudes had a range of 1800–2600 km from the equator. From year-to-year, the separation difference between these two average latitudes varied between 85 and 800 km (not shown) and averaged about 370 km (not shown) over the study period.

### 3.2 TC number trends

Of the 479 TCs in the study domain during the 1970–2017 study period, 94 (19.6 %) reached the stronger TC class and 385 (80.4 %) remained weaker TCs. The number of weaker TCs declined in each successive decade, while stronger TCs were relatively constant, except the 1970–1979 decade with only six stronger TCs (Table 1). Over the study period, the average season had about 9.98 TCs (Table 1), of which about 8.02 were weaker TCs and 2.02 were stronger

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**Fig. 3.** (a) Geographical distribution of TC genesis points (LGs; blue), (b) locations where lifetime-maximum TC intensity is reached ($LV_{\text{max}}$; red), and (c) number and percentage (in brackets) of LGs (blue letters) and $LV_{\text{max}}$ (red letters) in the subdomains of the study domain.
During this time, the annual number of TCs appears to have decreased by about 0.06 TC yr\(^{-1}\) (Fig. 5a). Annual numbers of weaker TCs (Fig. 5b) also decreased by 0.104 TC yr\(^{-1}\), whereas stronger TCs slightly increased by 0.04 TC yr\(^{-1}\) (Fig. 5c). The most active TC season was 1998, when a total of 18 TCs occurred, of which 14 were weaker TCs and 4 were stronger, although 1997 featured 16 TCs, of which 14 were weaker TCs and 2 were stronger TCs. The quietest TC season was 2012, with three weaker TCs and one stronger TC.

The annual number of weaker TCs varied widely, between zero and nine, in the six westernmost subdomains, whereas both the TC numbers and their variations were smaller in the NE, E, and SE subdomains (Fig. 6). Long-term decreases in annual TC numbers were apparent in the NW, N, W, C, and SW subdomains, the greatest of which was ~0.059 TC yr\(^{-1}\) in the W subdomain. The trends for stronger TCs appear to be positive and pronounced in the NW, N, W, and C subdomains, the greatest of these being 0.025 stronger TC yr\(^{-1}\) in the C subdomain. Stronger TCs were absent or nearly so in the other five subdomains.

### 3.3 TC intensity trends

The highest annual lifetime-maximum intensity (\(V_{\text{max}}\)) underwent a marked increase in the Southwest Pacific during the study period (Fig. 5d), suggesting
that TCs have become more intense at an estimated rate of about 0.778 knot yr\(^{-1}\). The highest \(V_{\text{max}}\) was 150 knots during TC Winston in 2016, and the lowest was 60 knots during TC Dora in 1971. The average annual lifetime-maximum intensity \((\bar{V}_{\text{max}}; \text{knots})\) had an upward trend of 0.266 knot yr\(^{-1}\) (Fig. 5e), which is consistent with the trend in \(V_{\text{max}}\) (Fig. 5d). The highest annual lifetime-maximum intensification rate \((\bar{I}R_{\text{max}}; \text{knot h}^{-1})\) generally had small variations (Fig. 5f, Table 2), and the long-term trend was almost zero (−0.001 knot h\(^{-1}\) yr\(^{-1}\); Fig. 5f); its highest value was 5.933 knots h\(^{-1}\) (35.6 knots (6h)\(^{-1}\)) during TC Veena in 1983, and the lowest was 1.35 knots h\(^{-1}\) (8.1 knots (6h)\(^{-1}\)) during TC Paula in 2001. There were 10 years (20.8 \%) with \(\bar{I}R_{\text{max}}\) values of < 2.5 knots h\(^{-1}\) (15 knots (6h)\(^{-1}\)) and 38 years (79.2 \%) with \(\bar{I}R_{\text{max}}\) values of ≥ 2.5 knots h\(^{-1}\), and in 22 years (45.8 \%) these \(\bar{I}R_{\text{max}}\) values occurred in the Cat 1 stage \((V < 48 \text{ knots})\) whereas in 26 years (54.2 \%) they occurred at Cat 2 or higher stages \((V \geq 48 \text{ knots})\). Some \(\bar{I}R_{\text{max}}\) calculations

![Fig. 5. Interannual variation in various metrics for TC activity during 1970–2017. (a) Number of TCs, (b) number of weaker TCs (Cat 1–3), (c) number of stronger TCs (Cat 4–5), (d) highest annual lifetime-maximum TC intensity \((\bar{V}_{\text{max}}; \text{knots})\), (e) average annual lifetime-maximum intensity \((\bar{V}_{\text{max}}; \text{knots})\), and (f) highest annual lifetime-maximum intensification rate \((\bar{I}R_{\text{max}}; \text{knot h}^{-1})\). The blue line shows the linear trend, and the number in the top left corner is its slope.](image-url)
may be influenced by evolving observation and analysis techniques.

3.4 TC days
An average of 42.8 TC days per year were recorded in the study period, of which 39.24 were weaker TC days and 3.56 were stronger TC days (Table 1). TCs with a lifetime of 2–4 TC days were the most frequent, accounting for 152 (~32%) of the 475 TCs (Fig. 7). Beyond four TC days, the frequency decreased exponentially with increasing TC lifetime. Only eight TCs had lifetimes greater than 14 TC days. The annual totals of TC days has generally decreased by about 0.352 day yr\(^{-1}\) (Fig. 8a); however, stronger TC days increased by about 0.087 day yr\(^{-1}\) (Fig. 8b). The largest number of total TC days per year was 88.5 days in 1972 (although 88.25 and 84.75 TC days occurred in 1998 and 1992, respectively), and the smallest number was 16.75 days in 2002. The largest number of stronger TC days was 15.5 days in 2005, and in 10 years, 7 of them in the 1970–1979 decade, there were no stronger TC days.

3.5 ACE trends
Although annual ACE was almost unchanged over the study period, did have a large year-to-year vari-

Fig. 6. Interannual variation in the number of TCs over the study subdomains. The blue dots represent weaker TCs and red bars represent stronger TCs. The numbers indicate the slopes of the linear trends of weaker TCs (trend1) and stronger TCs (trend2).
The annual maximum intensification rates ($\bar{IR}_{\text{max}}$). $V_{n-1}$ and $V_n$ are the wind speeds involved. The asterisks (*) indicate $IR_{\text{max}}$ values $\geq 4.0$ knots h$^{-1}$ or 24.0 knots (6h)$^{-1}$. Bold italics denote TCs that skipped an intensity category.

<table>
<thead>
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<th>Year</th>
<th>$V_{n-1}$</th>
<th>$V_n$</th>
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Fig. 7. Histogram showing frequency of TC lifetimes during 1970–2017.

Fig. 8. Interannual variation in total TC days during 1970–2017. (a) Total TC days for all TCs, (b) total TC days of stronger TCs (category 4–5; $V \geq 86$ knots). The numbers indicate the slope of the linear trend.
We conducted a correlation analysis (Fig. 10) to investigate the individual contributions from TC numbers, TC days, and TC intensity. The results showed that ACE is very strongly correlated with TC days ($r^2 = 0.841$), strongly correlated with stronger TC days ($r^2 = 0.653$), moderately correlated with stronger TC number ($r^2 = 0.461$) and TC number ($r^2 = 0.408$), and weakly correlated with $V_{\text{max}}$ (Fig. 10f; $r^2 = 0.275$) and $V_{\text{max}}$ (Fig. 10e; $r^2 = 0.276$). These results suggest that ACE is most strongly influenced by TC days and numbers.

### 3.6 PDI trends

The PDI time series also exhibits a large year-to-year variability, with a slightly upward long-term trend of $0.32 \times 10^5$ m$^3$ s$^{-3}$ yr$^{-1}$ (Fig. 9b). The highest value, $\sim 139 \times 10^5$ m$^3$ s$^{-3}$, was observed in 1998 and 1999, which is generally small.
the lowest, $\sim 9 \times 10^5 \text{ m}^3 \text{ s}^{-3}$, was observed in 1971. A periodicity of approximately 6–8 years in the PDI time series after 1990 is more evident than it was for ACE.

A correlation analysis (Fig. 11) showed that PDI is strongly correlated with strong TC days (Fig. 11d; $r^2 = 0.794$) and TC days (Fig. 11c; $r^2 = 0.677$), moderately correlated with stronger TC number (Fig. 11b; $r^2 = 0.548$) and $V_{\text{max}}$ (Fig. 11c; $r^2 = 0.409$), and weakly correlated with $\bar{V}_{\text{max}}$ (Fig. 11f; $r^2 = 0.367$) and TC number (Fig. 11a; $r^2 = 0.306$). The results show that, apart from the number of TC days, PDI is closely related to intense TCs (stronger TC number and $V_{\text{max}}$).

### 3.7 SST trends

The long-term time series of area-averaged SST (Fig. 12a) and SST anomaly (Fig. 12b) over the Southwest Pacific clearly show that SST has exhibited a stable increase since the mid-1970s. The SST anomaly changed from negative to positive in 1995. For the 1917–2017 period, the SST anomaly had a positive trend of 0.8°C above average per 100 years ($0.008\text{°C yr}^{-1}$). The strongest positive trend of 0.016°C yr$^{-1}$ was in the N subdomain. The NE and E subdomains had trends of 0.015°C yr$^{-1}$, the C and SE subdomains had trends of 0.014°C yr$^{-1}$, and the NW subdomain had a trend of 0.013°C yr$^{-1}$. The SST anomalies were generally near or below average until around 1995, when they began to be above average. The two most recent decades (2007–2017 and 1996–2006) are the warmest decades in the dataset. For the whole study period, 1978 ranks as the coldest year with an average SST of 25.18°C and 2017 is the warmest at 26.15°C.

The time series of the annual average SST over the nine subdomains are shown in Fig. 13. SSTs were lower in the SW, S, and SE subdomains, with values ranging between 21°C and 22°C. In the W, C, and E subdomains, SST varied between 26°C and 28°C. The NW and N subdomains had SSTs between 28°C and 30°C, and in the NE subdomain SST varied between 26°C and 29°C. The strongest positive trend of 0.016°C yr$^{-1}$ was in the N subdomain. The NE and E subdomains both had trends of 0.015°C yr$^{-1}$, the C and SE subdomains had trends of 0.014°C yr$^{-1}$, and the NW subdomain had a trend of 0.013°C yr$^{-1}$. The S, SW, and W subdomains had the weakest trends of 0.011, 0.01, and 0.006°C yr$^{-1}$, respectively.

Figure 14 shows scatter plots of the nine TC metrics against SSTs for the Southwest Pacific from 1970 to 2017. Clearly, SST has risen over the study period (color of dots), and we found that $\bar{V}_{\text{max}}$, was the most...
4. Discussion

The parts of the Southwest Pacific identified in this study (Fig. 3) as the most favorable TC genesis locations (the vicinity of Vanuatu, Gulf of Carpentaria, and northeastern Australia) were also highlighted in previous studies. Diamond et al. (2013) named the area centered around Vanuatu as the main TC development area for the Southwest Pacific region, and Vanuatu also was included in the domain of studies by Basher and Zheng (1995), Webster et al. (2005), Kuleshov et al. (2010), and Ramsay et al. (2014). Dare and Davidson (2004) named the Gulf of Carpentaria and the east coast of Australia as two of the three most-favored TC genesis locations for the Australian region. The Vanuatu area lies roughly between the W,
NW, N, and C subdomains, which have the highest concentration of genesis locations and $LV_{\text{max}}$ values. The W subdomain, in particular, has relatively large numbers of genesis locations and $LV_{\text{max}}$ values.

The approximately constant trend of genesis latitudes identified in this study (Fig. 4) is consistent with the results reported by Terry and Gienko (2010) for the tropical South Pacific (160°E–120°W, 0–25°S) from the 1969–1970 to 2007–2008 season. However, the migration rates of both genesis and $V_{\text{max}}$ latitudes in this study, which may be influenced by TC numbers, are considerably small compared to results found by Daloz and Camargo (2017) and Kossin et al. (2014), who linked the poleward migration to changes in environmental factors. The reasons for these disparities remain a continuing challenge.

Very generally, the overall number of TCs and weaker TCs are decreasing while stronger TCs are slightly increasing (Fig. 5). Similar trends were also reported by Webster et al. (2005). These findings are generally consistent with the projected number of storms as a consequence of climate change (Emanuel 1987; Elsner et al. 2006, 2008). However, Klotzbach (2006) found no significant trend over the South Pacific Ocean (5–20°S, 155–180°E) from 1985 to 2005, and Hoarau et al. (2018) also found no trend in the number of strongest TCs between 1980 and 2016. On the other hand, Murakami et al. (2014) reported upward trends of strong TCs in the North Atlantic. The reduction in the overall number of TCs and weaker TCs in the present study may be attributed to increased atmospheric stabilization due to weaker
lower troposphere warming and stronger warming aloft in the Southwest Pacific, as explained by Maru et al. (2018). The small number of stronger TCs in the 1970s may be an effect of then-current monitoring practices. As reported by Knaff et al. (2010), most WMO Regional Specialized Meteorological Centers and Tropical Cyclone Warning Centers have consistently used the Dvorak technique since the late 1980s. However according to Terry and Gienko (2010), since stronger TCs are generally longer lived than weaker systems, and pose a significant threat to lives and resources due to their destructive potential, there is a high degree of certainty that such TCs have been well captured in records.

The importance of the spatial distribution of TCs across the Southwest Pacific motivated us to analyze trends of weaker and stronger TCs over the nine sub-domains (Fig. 6). Generally, trends were negative for weaker TCs in all subdomains; however, they were more prominent in the W, NW, N, and C subdomains.

Fig. 14. Relationship between TC metrics and SST during 1970–2017. (a) highest annual lifetime-maximum intensity ($V_{\text{max}}$), (b) average annual $V_{\text{max}}$ ($\bar{V}_{\text{max}}$), (c) number of TCs, (d) number of stronger TCs (Cat 4–5), (e) highest annual maximum intensification rate ($IR_{\text{max}}$), (f) number of TC days, (g) number of stronger TC days (Cat 4–5), (h) ACE, and (i) PDI. The black lines show linear trend, and the numbers indicate the coefficients of determination. The color scale represents the time period of data points.
The upward trend of stronger TCs in the W, NW, N, and C subdomains is consistent with the rest of the Southwest Pacific. Furthermore, the annual variation in the number of TCs is quite consistent with the multi-decadal count (Table 1); however, advances in detection methodologies and changes in monitoring procedures may produce a bias toward recent decades since the newest TCs are more frequently and better sampled.

This study found that the annual $\hat{V}_{\text{max}}$ has trended upward in the Southwest Pacific (Fig. 5d). Kossin et al. (2013) also found an increasing trend for stronger TCs ($V \geq 65$ knots) but at a slightly slower rate of about 2.5 m s$^{-1}$ per decade (4.86 knots per decade). Strong TCs have also become more intense in the North Atlantic and Indian Oceans (Emanuel 2005; Elsner et al. 2008) and the northwest Pacific (Emanuel 2005; Mei and Xie 2016). TC Winston in 2016, with a $V_{\text{max}}$ of 150 knots, is the most intense Southwest Pacific TC in the dataset; in fact, TC Winston may be one of the strongest in the world. In addition, annual $\hat{V}_{\text{max}}$ has also increased. A drop in $\hat{V}_{\text{max}}$ values between 1996 and 2002 may be related to more weaker TCs (Cat 1–3) and fewer stronger TCs during these particular seasons.

While the long-term trend of $\hat{IR}_{\text{max}}$ is almost zero, large $\hat{IR}_{\text{max}}$ values have occurred in individual years at irregular intervals (Fig. 5f). Although most $\hat{IR}_{\text{max}}$ values (68.75 %) occurred during the Cat 1 and 2 stages (Table 2), TCs of at least Cat 2 strength were more likely to produce larger $\hat{IR}_{\text{max}}$ values ($\geq 4$ knots h$^{-1}$ or $\geq 24$ knots (6h$^{-1}$)). This result fits scenarios in which a storm skips an intensity category between measurement times. For example, TC Prema in 1993 jumped from 60 to 90 knots (Cat 2 to Cat 4), and TC Ita in 2014 went from 85 to 110 knots (Cat 3 to Cat 5). These results indicate that TC intensity is likely to govern $\hat{IR}_{\text{max}}$ and $\hat{IR}_{\text{max}}$ is likely to occur during a TC’s initial or immature stages when it is further from its $V_{\text{max}}$ and, thus, has a greater potential to intensify faster. A dependence of intensification rate on TC intensity (in addition to SST and TC structure) was also found by Xu and Wang (2018) over the Western North Pacific. Xu et al. (2016) also found a close relationship between SST and the intensification rate in the North Atlantic. In this study, we found very little connection between $\hat{IR}_{\text{max}}$ and SST (discussed shortly). Kowch and Emanuel (2015) reported global intensification rates are controlled by randomly distributed environmental and internal processes, and Wang et al. (2015) showed that SST, heat potential, vertical wind shear, and relative humidity are the main controlling factors over multiple decades. These studies suggest the intensification rate is controlled by other factors besides SST and can vary across regions.

Exposure to associated hazards is one important factor that contributes to the risk of being affected by a TC. Depending on environmental conditions, a TC can live for a short period or much longer. In this study, TC days decreased over the study period, while stronger TC days have increased (Fig. 8). Similar trends were found by Webster et al. (2005), not only for the Southwest Pacific but also in the North Pacific and Indian oceans. In the Western North Pacific, Kamahori et al. (2006) found an increasing trend in TC days of Cat 2 or higher (based on the Saffir-Simpson scale) over 30 years, based on both the Japan Meteorological Agency (JMA) and the JTWC dataset. However, for the case of very intense TC days (Cat 4 or higher), the JTWC dataset shows an increasing trend whereas the JMA dataset shows a decreasing trend.

The almost zero trend of ACE in the present study (Fig. 9a) is similar to the trends reported by Klotzbach (2006) and Chand and Walsh (2011, 2012) despite the differences in domains. In the present study, the contribution of TC days and stronger TC days to ACE is substantial. Contributions of TC numbers and stronger TC numbers are modest and, therefore, can be interpreted as secondary contributing factors. $\hat{V}_{\text{max}}$ and $\hat{IR}_{\text{max}}$ appear to have little connection with ACE. A periodicity of approximately 6–8 years, which is in phase with the 2–8 year ENSO band (Chand and Walsh 2011), may have contributed somewhat to the overall ACE trend. Note that TC occurrences in the South Pacific (east of 170°E) are higher in El Niño than in La Niña years (Kuleshov et al. 2008).

Although stronger TC days and TC days remained as the primary contributors to both ACE and PDI (Figs. 10, 11), intensity measurements ($\hat{V}_{\text{max}}$ and $\hat{V}_{\text{max}}$) were generally more strongly correlated with the latter ($r^2 = 0.409$ and 0.367, respectively) than with the former ($r^2 = 0.275$ and 0.276, respectively). This shows that PDI is roughly proportional to the power dissipation generated by a TC through higher wind speeds. In the North Atlantic and the Western North Pacific, PDI was influenced by intensity and lifetime (Emanuel 2005). In addition, Murakami et al. (2014) found that TC genesis is the primary contributing factor to both ACE and PDI in the North Atlantic, and other metrics, such as duration and intensity, were minor.

SST is well known to influence TC activity. The global relationship between the ocean’s thermal energy and TCs’ intensity has been documented in observations and model studies (e.g., Webster et al.
In this study, changes in SST were very similar to the global changes reported by the Fifth IPCC Report (Hartmann et al. 2013) and U.S. Environmental Protection Agency (2018). The notable spatial variations in SST between the equatorial region, which receives the greatest amount of solar radiation, and the poleward regions are believed to influence the average SST of the whole Southwest Pacific.

Our results suggest that, while SST may have contributed somewhat to $V_{\text{max}}$ and TC days, its contribution to other TC metrics is less clear. The aforementioned relationship between SST and $V_{\text{max}}$ is supported less strongly than prior studies have found in the Northern Pacific Ocean (e.g., Kuroda et al. 1998; Wada et al. 2012); however, this could be in line with Evans (1993)'s suggestion that SST may place an upper bound on storm intensity but is not a sufficient predictor of TC intensity. The negative correlation of SST with TC days indicates warmer SSTs may reduce the number of TC days through atmospheric stabilization (Sugi 2012). It also appears that TC activities in recent decades occurred more often at warmer SSTs.

5. Summary and conclusions

This paper presents a comprehensive study of the characteristics of TCs in the Southwest Pacific based on the SPEArTC best-track and ERSSTv5 dataset. The study examined a variety of TC metrics and linked them to the gradual rise in SST. Our choice of a larger study domain than previous studies may be an advantage over prior attempts as it includes more TCs. The main primary findings are:

- The W, NW, N, and C subdomains, typically west of Fiji, are the main hotspots for TC activity in the Southwest Pacific; thus, the risks and vulnerability of populations are highly elevated across these regions.
- The latitudes of both TC genesis and $V_{\text{max}}$ remained almost unchanged over the 1970–2017 study period, which suggests little shift in the dominant areas affected by TCs.
- Although the year-to-year fluctuation in the number of TCs in the Southwest Pacific is quite large, with a range of 4–18, we found a 48-year average of around 10 TCs (of which two were stronger TCs) per TC season. The overall number of TCs appears to have decreased. The number of stronger TCs have slightly increased but it is highly likely an artifact, possibly due to data uncertainties in the 1970s, which is consistent with Hoarau et. al (2018)’s study, which found no trends in the number of strongest TCs over the 1980–2016 period. However, the strength of stronger TCs have increased noticeably. Such high-impact events include TC Pam in 2015 with $V_{\text{max}} = 135$ knots and TC Winston in 2016 with $V_{\text{max}} = 150$ knots.
- Maximum intensification ($IR_{\text{max}}$) occurred at all TC stages (Cat 1 to Cat 5), but most (68.75 %) occurred during the Cat 1 and 2 stages. This indicates that weaker TCs may intensify faster because they are further from their peak intensity. However, larger $IR_{\text{max}}$ values ($\geq 4$ knots h$^{-1}$ or $\geq 24$ knots (6h)$^{-1}$) are likely to occur during TCs of at least Cat 2 strength, which suggests faster intensification rates may be somewhat related to the current TC stage. Because the highest $IR_{\text{max}}$ value in each year ($IR_{\text{max}}$) has no long-term trend, the occurrence of intensifying TCs with higher intensification rates is likely to continue.
- There are about 42.8 TC days (of which 3.56 were stronger TC days) per TC season in the Southwest Pacific. The most frequent TC length is 2 to 4 days. The total TC days ($V \geq 34$ knots) has decreased while stronger TCs ($V \geq 86$ knots) live longer.
- There are no apparent trends in ACE and PDI over the study period. The results also suggest both quantities are controlled mainly by TC days and secondarily by TC number and intensity; however, $V_{\text{max}}$ and stronger TC numbers tend to contribute more strongly to PDI than to ACE.
- The averaged SST exhibited a gradual warming trend of about 0.624°C over the past 48 years; however, this trend is only weakly correlated with TC activity. This finding suggests that, while SST may contribute to the uppermost TC intensity and fewer TC days, it does not appear to be the dominant environmental determinant of TC activity, nor does warmer SST alone necessarily explain TC activity trends.

Our findings are somewhat consistent with theoretical expectations of the change in TC activity under climate change, particularly in TC overall frequency and $V_{\text{max}}$ intensity. However, the small trends found in genesis latitude, $V_{\text{max}}$ latitude, $IR_{\text{max}}$, ACE, and PDI tell us that TC activity has not changed much, suggesting that the Southwest Pacific region is likely to remain most vulnerable to such TC impacts at irregular interannual periods.

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References


Hoarau, K., L. Chalonge, F. Pirard, and D. Peyrusaube, 2018: Extreme tropical cyclone activities in the south-


Murakami, H., T. Li, and P.-C. Hsu, 2014: Contributing factors to the recent high level of accumulated cyclone energy (ACE) and power dissipation index (PDI) in the North Atlantic. *J. Climate*, 27, 3023–3034.


Vincent, E. M., M. Lengaigne, C. E. Menkes, N. C.


