Tropical Cyclone Climatology of the South Pacific Ocean and Its Relationship to El Niño–Southern Oscillation

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ABSTRACT
Climatological features of tropical cyclones in the South Pacific Ocean have been analyzed based on a new archive for the Southern Hemisphere. A vortex tracking and statistics package is used to examine features such as climatological maps of system intensity, the change in intensity with time, average tropical cyclone system movement, and system density. An examination is presented of the spatial variability of these features, as well as changes in relation to phase changes of the El Niño–Southern Oscillation phenomenon. A critical line is defined in this study based on maps of cyclone intensity to describe the statistical geographic boundary for cyclone intensification. During El Niño events, the critical line shifts equatorward, while during La Niña events the critical line is generally displaced poleward. Regional variability in tropical cyclone activity associated with El Niño–Southern Oscillation phases is examined in relation to the variability of large-scale atmospheric or oceanic variables associated with tropical cyclone activity. Maps of the difference fields between different phases of El Niño–Southern Oscillation are examined for sea surface temperature, vertical wind shear, lower-tropospheric vorticity, and midtropospheric relative humidity. Results are also examined in relation to the South Pacific convergence zone. The common region where each of the large-scale variables showed favorable conditions for cyclogenesis coincided with the location of maximum observed cyclogenesis for El Niño events as well as for La Niña years.

1. Introduction
Tropical cyclones (TCs) are the most dangerous and damaging weather events to regularly affect tropical areas. In addition to the inherent difficulties associated with prediction of extreme events in general, historical records for the various TC basins demonstrate significant interannual variability in the temporal and spatial distribution of TCs. To improve the understanding of TC climatology and variability, and therefore ultimately reduce the risk and damage associated with TC occurrences, numerous studies on TC activity and development processes have been conducted in the various different ocean basins throughout the world.

A number of studies have focused on the relationship between TC activity and the El Niño–Southern Oscillation (ENSO) phenomenon. In the Northern Hemisphere a significant reduction (increase) of TC activity over the Atlantic basin is observed during El Niño (La Niña) events (e.g., Gray 1984; Shapiro 1987; Knaff and Sampson 2009). Significant spatial and temporal variations of TC activity over the western North Pacific associated with El Niño and La Niña events have also been reported (Chan 1985; Chan 2000; Wang and Chan 2002). Changes in the frequency of TCs over the north Indian Ocean have been studied using data from 1877 to 1998, and a reduction in TC activity over the Bay of Bengal in the months May to November during El Niños has been noted (Singh et al. 2000).
In the Southern Hemisphere (SH), Nicholls (1979) showed that the Southern Oscillation could be used to predict Australian tropical cyclone numbers. A relationship between cyclone formation and synoptic properties, such as the monsoon trough, was identified by McBride and Keenan (1982) from spatial clusters of cyclone genesis. Efforts to develop TC climatologies for the Australian region have been made since the 1980s. For example, Holland (1984) analyzed data for the period 1958–79, and Nicholls (1985) examined records of Australian TC numbers from 1909/10 to 1982/83. A nonlinear rising trend, with fewer TCs observed at the beginning of the century, was attributed by Nicholls to the improvements in observing systems and networks. However, strong interannual variability in TC activity occurs around this trend, and Nicholls et al. (1996) showed evidence of a strong statistical link between these interannual fluctuations of TC numbers in the Australian region and the Southern Oscillation, as well as the sea surface temperature (SST) in the northern Australian region. Goebbert and Leslie (2010) investigated the influence of ENSO on TC activity in the eastern region of the south Indian Ocean with a view toward developing seasonal prediction schemes.

In the South Pacific Ocean (SPO), it is known that El Niño events can cause TC activity to occur farther eastward than normal and also bring about a general suppression of TC activity in the Coral Sea (Gray 1988). The surveys by Kerr (1976), Revell (1981), Revell and Goulter (1986), and Thompson et al. (1992) present a comprehensive continuous study on western South Pacific TCs over the period from 1936 to 1989. An increase in TCs during the 1979–89 decade relative to the previous decade was reported by Thompson et al. (1992). It was suggested that the increase in frequency of TCs is most likely an indication of the interannual variation in the large-scale tropical circulation anomalies associated with the Southern Oscillation. Bashier and Zheng (1995) analyzed spatial patterns and relationships of TCs in the western South Pacific with respect to the Southern Oscillation and SSTs, and found that the geographical distribution of TC incidence shifts eastward (westward) and northward (southward) during negative (positive) Southern Oscillation phases, as indicated by the Southern Oscillation index (SOI). They also concluded that the primary influence on TC incidence west of 170°E was the local oceanic conditions, while to the east of 170°E it was the eastward extent of favorable atmospheric conditions, as indicated by the SOI or Tahiti mean sea level pressure.

Terry (2007) presented a TC climatology in the SPO and found that January and February, when the South Pacific convergence zone (SPCZ) moves to its most southerly average position, was the most likely period for TC occurrences. That study also showed that the interannual variability in TC numbers is mostly related to ENSO events, confirming earlier results. TCs also tend to form and develop farther equatorward during El Niño events. Previous studies have also investigated large-scale environmental parameters influencing TC genesis and development processes. For example, Venthem and Wang (2007) examined large-scale environmental flow patterns around western North Pacific tropical storms and found that the low-level combined monsoon confluence–shearline pattern was very important for TC rapid intensification at their early stage of development.

These earlier studies have focused mainly on spatial variations in TC occurrence. The results presented here for this study examine a wide range of TC characteristics—including TC transport, intensity, and temporal changes in intensity, genesis, and system density—with the analysis taking into consideration the interrelationship between the various different TC climatological features. Additionally, the study is based on a new comprehensive best-track TC database for the Southern Hemisphere, with a uniform statistical approach [based on a vortex tracking and statistics package updated from Murray and Simmonds (1991) and Jones (1994)] used to generate climatological TC characteristics in the SPO.

2. Data and methodology

To explore the climatological characteristics and fluctuations of observed TC activity, a reliable and “homogeneous” TC database is essential. An early attempt to develop a TC archive for the South Pacific and south Indian Oceans (i.e., an area south of the equator, 30°E–120°W) was made by Kuleshov and de Hoedt (2003). More recently, the TC archive for the SH (the SHTC) has been compiled at the National Climate Centre of the Australian Bureau of Meteorology (Kuleshov et al. 2008; Kuleshov et al. 2009). This archive has been updated as presented in this paper to include best-track data up to the 2009/10 TC season. TC track data are drawn from the National Meteorological and Hydrological Services of Australia (Bureau of Meteorology), New Zealand (Meteorological Service of New Zealand), and France (Météo-France), and are then combined into one best-track dataset. The dataset now covers 41 TC “years” from 1969/70 to 2009/10, with the TC year in the SH taken as the 12-month period from July to the following June inclusive. A more specific TC “season” is taken here to mean the 6-month period from November to April. This study does not specifically examine TC
activity for the Australian region, although it does examine TC activity in areas off the east coast of Australia (such as the Coral Sea), with the SPO being referred to throughout this paper to include ocean regions as far west as the east coast of Australia.

Based on the data from the SHTC archive, the current study is aimed at summarizing the extensive existing knowledge and applying a uniform approach to the analysis of TC activity in the SPO. The SPO is defined here as the area east of 135°E, derived from the longitude of local minimum in the average annual number of TCs (Kuleshov et al. 2008). In an effort to minimize the impact of satellite-induced inhomogeneities in the SHTC archive, we use the 1969/70–2009/10 period for our analyses of location information, and the 1981/82–2009/10 period for the analysis of intensity information. The first period marks has largely complete satellite coverage based from polar-orbiting satellites, while the second period has largely complete coverage from Geostationary Meteorological Satellites (GMS) (Kuleshov et al. 2010).

To analyze the climatological characteristics of the SHTC archive, we apply a vortex-tracking software package, originally developed at The University of Melbourne, Australia, for the detection and tracking of vortices in gridded pressure fields and the like, and then further developed and updated at the Australian Bureau of Meteorology (Murray and Simmonds 1991; Jones 1994). This vortex tracking package has been used extensively for the analysis of cyclones across particularly high latitudes (e.g., Jones and Simmonds 1993; Pezza et al. 2007). As the TC track data are already available, only the statistical analysis part of the vortex tracking package is used in this study.

Both spatial and temporal statistics are derived from the individual TC positions using a dual process of interpolation. The first step involves interpolation in the time domain using bicubic splines to compute the intermediate data along the tracks based on the raw system positions to provide smoothly varying statistics. The data in the SHTC archive along TC tracks occur at varying frequencies (though most commonly with TC positions every 6–12 h), and this has been interpolated to a consistent frequency of 6-hourly positions. Positions in latitude–longitude and central pressure (taken as an estimate of intensity) are both interpolated. The second interpolation involves the distribution of data from the observed and interpolated positions using a Cressman weighting (Cressman 1959). TC characteristics such as system flux, system intensity, intensity tendency, and system density are then computed using the methodology described in detail by Jones (1994). A summary of the calculations applied is included for reference in the appendix.

In addition to spatial variations in climatological features, such as those described above, the variability due to changes in the phase of ENSO is also examined. There is no universally agreed method for measuring the strength of ENSO and/or defining its phases, which creates some confusion when comparing studies. In this study, we used a list, derived by Kuleshov et al. (2009), of TC seasons (i.e., spanning the SH summer period) that are characterized predominantly by El Niño or La Niña events. These definitions used a comprehensive analysis of six ENSO indices [the SOI; Niño-3, Niño-4, and Niño-3.4 indices; multivariate ENSO index (MEI); and five-variable ENSO index (5VAR)] and was recommended for subsequent studies on TCs in the SH. The El Niño TC seasons for this study are 1969/70, 1972/73, 1976/77, 1977/78, 1979/80, 1982/83, 1986/87, 1987/88, 1991/92, 1992/93, 1993/94, 1994/95, 1997/98, 2002/03, 2004/05, 2006/07, and 2009/10, while the La Niña TC seasons are 1970/71, 1973/74, 1974/75, 1975/76, 1988/89, 1998/99, 1999/2000, and 2007/08. Of the 41 seasons (from 1969/70 until 2009/10), there are 16, not classed above as El Niño or La Niña, that are referred to here as neutral seasons. However, the focus of this study is primarily on the impact of the two extreme phases of ENSO (El Niño and La Niña), rather than the neutral phase, on characteristics of TC occurrence and their relationship to large-scale environmental parameters. Additionally, the influence of other types of El Niño, such as the El Niño Modoki (e.g., Trenberth and Stepaniak 2001; Larkin and Harrison 2005; Ashok et al. 2007), is not examined.

We note that there is a distinct mismatch in the number of El Niño (17) and La Niña (8) events over recent decades. It has been widely documented that the Pacific basin has seen a shift toward a more El Niño–like state in recent decades reflected by trends in sea surface temperatures, wind patterns, and the SOI (e.g., Power and Smith 2007; Power and Kociuba 2010). This factor is taken into consideration when drawing conclusions from the results presented in this paper, such as when interpreting some small-scale variability, particularly for La Niña seasons.

3. Results

To illustrate data sampling and broad features, tracks of TCs in the SPO are shown in Fig. 1 for the entire 41-yr study period from 1969/70 to 2009/10 (Fig. 1a), for the 17 TC years characterized by El Niño–affected seasons (Fig. 1b) and for the eight La Niña seasons (Fig. 1c). The TC tracks cover a region south of the equator extending into the central SPO (to around 110°W). Although the SPO is the focal region of this study, the figures extend farther westward than this to allow for a larger-scale
perspective to be obtained for features occurring in the far west SPO. Major climatological features are clearly evident in the TC tracks, such as the distinct lack of systems toward the east Pacific cold tongue and high activity in the Coral Sea.

Many authors have previously noted the shift in TC activity in the Pacific associated with variations in ENSO. While noting the imbalance in the number of El Niño and La Niña years, the tracks show a noticeable displacement toward the southwest during La Niña events compared to El Niño events, in agreement with previous studies (Evans and Allan 1992; Basher and Zheng 1995; Terry 2007; Kuleshov et al. 2008). The influence of ENSO on TC activity is examined in more detail in this section, including the spatial characteristics of TC transport, system density, intensity, and temporal changes in intensity and genesis regions.

a. System transport

System transport fluxes measure the average net TC movement as defined in the appendix. The transport of TCs is largely dependent on the environmental steering flow in which they are embedded (Chan and Gray 1982), and TC dynamics such as the beta effect, which leads to a southwest drift in the SH (Chan and Williams 1987; Emanuel and Nolan 2004).

Figure 2 shows the average system fluxes for all TC seasons investigated in this study (Fig. 2a), as well as separately for both the warm and cold ENSO phases.
(Figs. 2b,c, respectively). In terms of the climatology for all years (Fig. 2a), the flux vectors in the SPO to the west of the date line are generally oriented toward the southeast, while to the east of the date line the vectors are oriented toward the south. The region of maximum net flux is located near New Caledonia at $165^\circ$E.

The TC transport fields during El Niño years (Fig. 2b) show that the maximum in TC transport is stronger during El Niño years, and centered closer to the date line (at around $15^\circ$S, $170^\circ$E), than for the climatology based on all years (Fig. 2a). The meridional component of the transport vector fields during El Niño years is oriented in a southerly direction throughout the SPO, as was also the case for the climatology. In contrast to the meridional component, the zonal component of the transport vector fields during El Niño years is oriented in a southerly direction throughout the SPO.

During La Niña years (Fig. 2c), increased fluxes occur over the Coral Sea and around New Caledonia compared to the other ENSO phases. The direction of the meridional component of the average TC transport during La Niña years is consistent with the case for El Niño years and the climatology based on all years, being southward throughout the SPO. However, the magnitude of the meridional component is notable during La Niña years in that it is quite strongly southward to the northeast of New Zealand. The zonal component of the flux vector is more similar to the climatology than was the case for El Niño years, with a significant eastward component in the region to the west of the date line but very weak zonal movement in the region to the east of the date line.

Some unique characteristics are apparent during La Niña years in the zonal component of the transport vector fields, with a strong westward region in the Coral Sea in the far west of the SPO, forming part of a larger-scale region of curvature in the transport fields around this area.

In general, TC transport is noticeably higher in the SPO in El Niño years than in La Niña years, with the major difference located around $170^\circ$E over the SPO. It is noted that what Fig. 2 shows is the average annual system flux/transport, and in some areas, for example, between $140^\circ$ and $150^\circ$E in Fig. 2a, the southwesterly movements of TCs may be partially offset by south-easterly movements of others. The net result of such cases results in a southerly transport vector, noting that this does not necessarily mean that TCs in regions such as this only move southward. However, the results presented here correspond well with the TC track distributions presented in Fig. 1. The difference in average annual TC transport between El Niño years and climatology demonstrates increased fluxes located over the SPO at $170^\circ$E. For La Niña years, markedly increased fluxes are observed over the Coral Sea, around New Caledonia, and northwest of New Zealand.

### b. TC density

The TC density statistic is a measure of the sum of total TC occurrences in a given grid box. Average annual TC density (climatology) for the period from 1969/70 to 2009/10 TC years is presented in Fig. 3a. In the SPO, the area of highest TC density is located in the latitudinal belt between about $10^\circ$ and $20^\circ$S, and falls away sharply toward $30^\circ$S and over Australia. The decline as one moves south relates to both a tendency for systems to weaken as they move toward the less favorable subtropics, and also the generally fast rate of movement, while noting that track sinuosity generally decreases in a poleward direction (Terry and Gienko 2011). The extratropical transition of TCs (e.g., Sinclair 2002) is not a focus of this study, and characteristics of this change toward baroclinic forcing are not examined here.

In El Niño years (Fig. 3b), the band of high TC density intensifies compared to the climatology, although the location of maximum TC density remains relatively unchanged in latitude. The intensification results in the
area of the high TC density (e.g., greater than about 0.2 TCs per degree latitude squared) extending farther eastward to around 150°W. In La Niña years (Fig. 3c) there is a noticeable shift in TC density away from the equator and an overall reduction in numbers in more tropical areas. TC density is higher than climatology in parts of the western SPO (i.e., west of the date line) but generally lower than that in El Niño years. It is only near Australia that we find a greater number of TCs during La Niña years when compared to El Niño, consistent with the earlier study of Kuleshov et al. (2009).

The variation of TC system density is due to a number of different factors, including where TCs form and decay, where they move to, and how fast they move after formation. It is therefore useful to consider the new transport fields (Fig. 2) when examining the system density fields. For example, the maximum system density occurs for La Niña years in a region between New Caledonia and Vanuatu, ~165°W, which coincides with a “focal point” of the transport fields where TCs tend to move toward this location from the north and also from the northwest. Similarly for El Niño years, the maximum in system density (~160°W) coincides with a focal point in the TC transport fields with TCs moving to this region from the northwest, north, and northeast.

c. TC intensity

As mentioned in section 2, more reliable TC intensity records are available from 1981/82 to 2009/10, being the period of continuous geostationary satellite coverage. During this 20-yr period there are 12 TC years characterized by El Niño conditions and only 4 TC years characterized by La Niña conditions. Owing to the relatively limited amount of data available for La Niña years, combined with the lack of TC activity in the eastern Pacific during La Niña years, it is not possible to produce gridded spatial fields of intensity information that provide a reasonable indication of climatology, so areas east of 160°W are not examined here for La Niña years.

The average annual TC intensity during the 1980/81–2009/10 TC years is presented in Fig. 4a. Latitudinal variations in the average annual TC intensity show strong symmetry across 20°S latitude. As TCs originate in the near-equatorial zone and then typically move poleward (see Fig. 1), this demonstrates that TCs intensify while moving in the region between the equator and about 20°S, and then decay as they encounter cooler SSTs and enhanced westerly wind shear in the higher latitudes (as investigated later in this paper in the section on large-scale environmental influences). There are two major centers of TC minimum central pressure in the SPO (with a climatological average of 980–975 hPa) located along approximately 20°S and positioned around 165°E and 155°W, though noting that the eastern minimum is based on a modest number of systems.

Changes in the ENSO phase significantly affect the distribution of TC intensity. The average annual TC intensity for El Niño years is shown in Fig. 4b. The area of TC intensity with mean central pressure from 980 to 970 hPa covers a larger region than for the climatology based on all years, extending from around 150°E to 135°W along 20°S. In La Niña years (Fig. 4c), the area of very low central pressures is substantially contracted.
westward, with a region of maximum intensity centered at around 20°S, 160°E, while the region with central pressures of about 985–990 hPa extends farther southward, as compared to El Niño years.

d. Intensity tendency

The intensity tendency statistic measures the change in central pressure with time of individual systems (i.e., the rate of intensification or weakening). Figure 5a provides the average intensity tendency fields, showing the spatial distribution of areas favorable for the intensification (or weakening) of TCs systems. A remarkably clear boundary is apparent for the region of intensification, occurring in most areas north of −20°S. This boundary is defined here as a “critical line”—a statistical geographic boundary for TC intensification. The region where the fastest intensification tends to occur is over the central SPO at −10°S, with maximum values of the order of −10 hPa day⁻¹. Another local maximum in intensity tendency is apparent in the east-central Pacific near 10°S, 140°W. This feature is due to the El Niño years, as can be seen from the similarity in this region between Figs. 5a and 5b.

For El Niño years the magnitude of the intensity tendency field is broadly similar to the climatology based on all years. There is some indication that the critical line shifts equatorward. Conversely, during La Niña years the critical line is displaced poleward. The region of maximum intensification during La Niña years is confined to the western SPO (centered on about 15°S), whereas in other years it extends into the east SPO and is centered on −10°S.

e. TC genesis

The average annual TC genesis density is shown in Fig. 6 for different ENSO phases, based on the location where a system first reaches a central pressure less than 995 hPa. This is shown for the period from 1981/1982 to 2009/2010 (i.e., the period of reliable central pressure data).

TC genesis is highest along latitudes 10°–15°S in the SPO, with the exception of the region east of the date line during La Niña seasons when the region of peak genesis occurs farther southward at −15°–20°S. There is also some indication that the peak region of genesis occurs slightly farther northward during El Niño seasons than during the other phases of ENSO. The spatial extent of TC genesis regions during El Niño seasons extends farther east in the SPO, out to −135°W, in comparison with the other ENSO phases. There is a peak in TC genesis for El Niño seasons at −170°W, whereas during La Niña seasons the peak genesis occurs further west around 160°E in the Coral Sea.

4. Large-scale environmental influences

To relate changes in TC characteristics to the ENSO-related changes in oceanic and atmospheric conditions, several large-scale environmental parameters that influence TC development have been examined in this study. ENSO is a coupled ocean–atmosphere phenomenon: warming (cooling) in the Pacific (equatorial or near-equatorial regions) occurs in El Niño (La Niña)
years and these changes in ocean temperatures are coupled with significant changes in atmospheric circulation patterns. Gray (1979) demonstrated that the climatological aspects of the seasonal frequency of TC formation are closely connected to a number of large-scale environmental parameters including ocean thermal energy, the tropospheric vertical wind shear, the Coriolis parameter, low-level relative vorticity, relative humidity in the midtroposphere, and the difference in equivalent potential temperature between the surface and 500 hPa. More recently, Emanuel and Nolan (2004) developed a genesis potential index (GPI) empirically relating spatial and temporal variability of genesis to environmental predictors, such as the magnitude of vertical wind shear from 850 to 200 hPa, absolute low-level vorticity (850 hPa), relative humidity at 600 hPa, and potential intensity. The Gray TC genesis index and the GPI have some similarities, with the main difference in describing the thermodynamic environmental forcing.

Camargo et al. (2007) used the GPI to diagnose the ENSO effects on TC genesis and concluded that vertical wind shear and midtropospheric relative humidity are consistently important environmental contributors to TC genesis. Vorticity anomalies contributed most significantly in the central Pacific (Camargo et al. 2007), where during El Niño events TCs tend to form nearer the equator.

Based on the findings of these earlier studies, we selected sea surface temperature, vertical wind shear, lower-tropospheric vorticity, and midtropospheric relative humidity as primary large-scale environmental parameters to examine in relation to their potential contribution to variations in TC characteristics. The influence of the South Pacific convergence zone is also examined. National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996) are used to examine these large-scale environmental parameters, based on composites for the months from November to January. These months represent the first half of the TC season in the SH and are used here instead of the entire SH TC season (from November to April) so that the large-scale environmental parameters can be examined with only a small amount of modification due to the resultant TC activity. Composites for these months of the large-scale environmental parameters are examined in the following subsections.

a. Sea surface temperature

One of the necessary thermodynamic conditions for TC development is sufficient ocean thermal energy. In the SPO warming (cooling) of SSTs in equatorial and near-equatorial regions associated with El Niño (La Niña) can significantly influence TC genesis and development. In the current climate, TCs develop over near-equatorial regions with SSTs typically exceeding 26.5°C (e.g., Gray 1979, 1988). However, once developed, TCs typically move poleward out of their genesis regions into higher latitudes, often traveling long distances over waters with lower SST before they fully decay or undergo extratropical transition.

Figure 7 shows the average SST for the months from November to January (1969/70–2009/10), calculated separately for El Niño and La Niña years. For El Niño years, the “cold tongue” of SSTs (i.e., cold enough to suppress TC genesis) is contracted toward the South American coast westward with the 26°C contour near 120°W. In contrast, for La Niña years the cold tongue reaches much farther west into the Pacific to about 120°W. In contrast, for La Niña years the cold tongue reaches much farther west into the Pacific to about 180°. The ENSO influence on SSTs is therefore one potential explanation for the difference in TC activity between ENSO phases seen in the previous section, with genesis occurring farther east in the SPO during El Niño years (out to ~130°W) than for La Niña years (out to ~160°W). In La Niña years TC activity in the region north of 15°S and east of 180° is clearly suppressed.
Regional features that were apparent from the TC genesis climatology (Fig. 6) appear to be consistent with the ENSO influence on SST. For example, the 26°C contour of SST occurs at ~20°S; as previously noted, cyclones tend to weaken quite quickly as they pass south of this latitude. Additionally, in the Coral Sea region in the far west SPO, the warm (cold) SST anomalies during La Niña (El Niño) years are consistent with increased (decreased) TC genesis in this region. For longitudes around the date line, warm (cold) SST anomalies during El Niño (La Niña) years are once again very consistent with increased (decreased) TC genesis.

There is a strong latitudinal gradient throughout the central and western SPO, with little longitudinal variation, for all phases of ENSO. Given that warm SSTs are essential for TC genesis and intensification, this is consistent with the region of intensification being confined to latitudes equatorward of ~20°S, as shown by the “critical line” in Fig. 5. The SST variation with ENSO phases (Fig. 7c) shows that positive (negative) departures dominate the SPO north of a line from 15°S, 180° to 20°S, 120°W during El Niño (La Niña) years, while negative (positive) departures are located to the south of this line. This is consistent with the northward (southward) shift during El Niño (La Niña) years in the critical line defining the region of TC intensification, as well as shift in the genesis region and southward penetration of TCs.

b. Vertical wind shear

Weak to moderate vertical wind shear is one of the key environmental factors that promotes the development and intensification of TCs (e.g., Gray 1979; Emanuel and Nolan 2004). Vertical wind shear, calculated here as the magnitude of the vector difference between monthly mean winds at 850 and 200 hPa for November–January, is presented in Fig. 8 for different ENSO phases. The climatological mean in the belt between the equator and 15°S is between 5 and 15 m s\(^{-1}\). The lowest shear, between 5 and 10 m s\(^{-1}\), occurs in a transition zone between 200-hPa westerlies (poleward of 14°S) and easterlies (equatorward of 8°S). At 850 hPa this same low-shear region occurs where the easterly trade winds meet monsoon westerlies.

During El Niño seasons the vertical wind shear is anomalously low over the central Pacific Ocean (0°–15°S, near the date line), creating a more favorable environment for TC development (Fig. 8a), all other factors being equal—consistent with the peak in TC genesis in this region (see Fig. 6). In La Niña years the vertical shear anomalies are essentially opposite to the El Niño–shear relationship with anomalously high shear over the central Pacific north of about 15°S and anomalously low shear over the Coral Sea and the western SPO, extending northward over Papua New Guinea. This is once again consistent with the TC genesis seen during La Niña years. The shear at ~140°W along ~10°S is not remarkably low and therefore not likely related to the local maxima in intensity tendency (from Fig. 5) at this location.

Similar to the case for SSTs, the mean wind shear fields are consistent with the region of intensification, favoring latitudes closer to the equator throughout the western and central SPO. The wind shear variation with ENSO phases (Fig. 8c) shows that negative (positive) departures dominate the northern regions of the SPO (north of a line from 15°S, 180° to 20°S, 120°W) during El Niño (La Niña) years, while negative (positive) departures are located to the south of this line. This is consistent with the northward (southward) shift during El Niño (La Niña) years in the critical line defining the region of TC intensification, as well as latitudinal shifts in the regions of maximum genesis, intensity, and system density. Comparison with the earlier SST analyses shows that both wind shear and SST changes tend to vary in ways which a complimentary.

c. Lower-tropospheric relative vorticity

Relative vorticity fields, calculated at 850 hPa for the months from November to January are presented in Fig. 9
for different phases of ENSO. Cyclonic vorticity (i.e., negative values for the SH) is more favorable for cyclogenesis than anticyclonic vorticity (e.g., Camargo et al. 2007; Gray 1979, 1988). In the SPO the region of the strongest cyclonic vorticity occurs close to Papua New Guinea, possibly the result of the mountainous terrain, suggesting that local orographic effects may dominate the changes in the broader-scale circulation associated with El Niño. This region of favorable cyclonic vorticity for TC genesis extends from the Coral Sea eastward into the SPO, with a greater extent into the SPO during El Niño years (out to \(160^\circ W\)) than during La Niña years (out to \(170^\circ E\)) for latitudes where TC genesis is common (e.g., \(10^\circ S - 15^\circ S\) from Fig. 6). This variation in the central SPO region is broadly consistent with genesis variations with ENSO phases in this region. In other words, the enhanced (reduced) low-level vorticity during El Niño (La Niña) years in the central SPO is consistent with the eastward expansion (westward contraction) of TC activity in this region.

The difference in the vorticity fields between El Niño and La Niña seasons is presented in Fig. 9c. Equatorward of \(10^\circ S\) in the western SPO and \(15^\circ S\) in the central SPO, there is increased (decreased) cyclonic vorticity during El Niño (La Niña) years, with the opposite being the case poleward of these regions. However, this gradient does not persist to latitudes around \(20^\circ S\), suggesting that relative vorticity does not play a large role in defining the ENSO-dependent shift in the critical line defining the southern climatological boundary of intensification (from Fig. 5c).

d. Midtropospheric relative humidity

Relative humidity in the midtroposphere is one of the key factors influencing TC development, with high values of relative humidity being necessary to overcome the negative effects of entrainment on convection during the TC development stage (Gray 1979, 1988). During El Niño seasons, negative anomalies (relatively dry areas) can be found over the tropical regions from the western SPO out to \(160^\circ W\), reflective of the increased large-scale subsidence associated with a weakened or even reversed Walker circulation. This is consistent with several previous studies on the relationship between rainfall patterns and ENSO (e.g., Nicholls et al. 1996; Kane 1997), as well as with studies on TCs in the Australian region during El Niño seasons that show a substantial decrease in TC activity (e.g., Solow and Nicholls 1990; Kuleshov et al. 2008; Ramsay et al. 2008).

Figure 10 displays the relative humidity composites at 600 hPa during different ENSO phases. In general, the relative humidity fields are less consistent with expectations based on the climatological features of TC activity than the other large-scale environmental parameters.
examined previously. For example, the region with relative humidities above 60% extends farther east into the SPO during La Niña seasons than during El Niño seasons. There are, however, some regions where the relative humidity fields show features consistent with what would be expected to produce the observed ENSO variations in TC activity, for example, positive anomalies of relative humidity during La Niña seasons in the Coral Sea and during El Niño seasons east of the date line, corresponding to increased TC activity.

The relative humidity fields do not display as strong a latitudinal variation in the SPO, suggesting that they are not likely to play a significant role in defining the strong latitudinal stratifications of intensity tendency and genesis, as well as the resultant intensity and system density fields. Similarly, the variation in relative humidity with ENSO phases (Fig. 10c) is not consistent with the equatorward (poleward) shift in TC activity during El Niño (La Niña) seasons. For example, relative humidity is lower during El Niño than La Niña seasons throughout the central SPO poleward of $\sim 5^\circ$–$10^\circ$S, which would be expected to produce a reduction in TC genesis in contrast to what is actually observed (from Fig. 6). Additionally, the regions of local maxima in TC genesis for the different ENSO phases do not correspond to regions of increased relative humidity.

e. South Pacific convergence zone

The SPCZ is a favorable region for TC genesis in the SPO. It is a persistent and greatly elongated zone of low-level convergence characterized by strong convective activity and cloudiness (Kiladis and Diaz 1989; Vincent 1994). It extends from the west Pacific warm pool (approximately $140^\circ$E near the equator) toward the French Polynesian region ($\sim 120^\circ W$ at $30^\circ$S). The western part of the SPCZ is thought to be influenced by SSTs and orographic features in the region, while the more eastern portion of the SPCZ is thought to be dependent on interactions with higher latitude depressions (Kiladis et al. 1989) and on a dry zone in the eastern Pacific related to the Andes mountain range (Takahashi and Battisti 2007).

There are a number of different ways that the SPCZ is commonly represented in the literature, including spatial fields of rainfall anomalies, outgoing longwave radiation, and the convergence of the lower-tropospheric mean winds. Figure 11 shows the divergence of the 850-hPa wind fields for different phases of ENSO. The SPCZ can be seen as a region of enhanced convergence (i.e., negative values of divergence) that is present in the mean, El Niño, and La Niña years.

Consistent with the results of other studies (Folland et al. 2002; Vincent et al. 2009; Widlansky et al. 2011), the position of the SPCZ varies significantly with variations of ENSO. The SPCZ is stronger and displaced to the southwest during La Niña years compared to El Niño years. It is stronger in the eastern SPO during El Niño years compared to La Niña years: for example, the $-2 \text{ s}^{-1}$ contour extends to longitude $\sim 140^\circ W$ for El Niño years compared with $\sim 150^\circ W$ for La Niña years. In contrast, the SPCZ is stronger in the western SPO than during El Niño years; for example, the $-2 \text{ s}^{-1}$ contour extends westward during La Niña years all of the way to Papua New Guinea, in comparison to El Niño years when it only extends westward to longitudes around the date line. Figure 11c also shows a shift in the region of maximum convergence depending on the phase of ENSO, with a northeast (southwest) shift in the for El Niño (La Niña) years.

The spatial variation in the position of the SPCZ for different ENSO phases is broadly consistent with expectations based on the observed variation in TC activity, including the northeast (southwest) shift for El Niño (La Niña) years and the region of enhanced genesis in the Coral Sea during La Niña years and at $\sim 170^\circ W$ during El Niño years. However, as the SPCZ is oriented diagonally across the Pacific, it is less likely than some of the other more zonally stratified environmental parameters, such as SST (Fig. 7) and wind shear.
their contributions to variations in TC characteristics scale environmental parameters in order to examine humidity are investigated in this paper as primary large-tropospheric vorticity, and midtropospheric relative system density fields show an area of highest TC intensity, as measured by central pressure, tends to a new homogenous TC record. Spatial features of the climatologies were examined and notable differences found when TC years (from July to June) are grouped by ENSO phase.

5. Summary and conclusions

A comprehensive TC climatology for the SPO was examined, including TC genesis, system transport, intensity, intensity tendency, and system density, based on the application of a vortex tracking and statistical package to a new best-track database for the SH applied to a new homogenous TC record. Spatial features of the climatologies were examined and notable differences found when TC years (from July to June) are grouped by ENSO phase.

- TC genesis is mostly confined to the region from $\sim 5^\circ$ to $20^\circ$S in the SPO, with a northeast (southwest) shift tending to occur during El Niño (La Niña) years.
- The TC transport flux fields are generally stronger during El Niño conditions, with a stronger eastward component in the east SPO, in comparison to other ENSO phases. The meridional component of the TC transport flux is southward for all ENSO phases throughout the SPO, with a region on enhanced magnitude occurring for La Niña years northwest of New Zealand. A region of curvature in the fields is apparent, varying in position from the far west SPO (i.e., the Coral Sea) during La Niña years to $\sim 160^\circ$E in the central SPO during El Niño years.
- A boundary for the region of intensification occurs near $20^\circ$S that moves slightly poleward during La Niña years and slightly equatorward during El Niño years.
- TC intensity, as measured by central pressure, tends to peak near $20^\circ$S with embedded pressure minima near $165^\circ$E and $155^\circ$W. In tropical areas TCs tend to be more intense during El Niño years across almost the entire SPO, while slower rates of decay tend to mean TCs are a little strong in more southerly latitudes.
- System density fields show an area of highest TC density located in the latitudinal belt between $10^\circ$ and $20^\circ$S. This band of peak system density is generally stronger during El Niño years, located slightly poleward during La Niña years, as compared to the climatology based on all years. Also noticeable is an expansion poleward of higher TC frequencies in the southern Coral Sea and Tasman Sea during La Niña years.

Sea surface temperature, vertical wind shear, lower-tropospheric vorticity, and midtropospheric relative humidity are investigated in this paper as primary large-scale environmental parameters in order to examine their contributions to variations in TC characteristics related to ENSO. SST, relative vorticity, and wind shear showed a high degree of consistency with the features of the TC climatologies described above, based on their expected influence on TC activity following studies such as Gray (1979, 1984, 1988) and Camargo et al. (2007).

In contrast, relative humidity did not show as much consistency with the TC climatological features apparent for the other large-scale environmental parameters. The relationship between the SPCZ and ENSO was also broadly consistent with TC activity for different ENSO phases, with a northeast (southwest) shift in TC activity for El Niño (La Niña) years. However, there were also some features that were not found to be consistent in location/magnitude with any notable features of the various different environmental parameters examined. For example, the region of increased TC activity (including a local maxima in intensity tendency) for El Niño years at $\sim 140^\circ$W does not coincide in position with local maxima in any of the large-scale environmental variables (or the SPCZ) investigated in this study.

For SST and the vertical wind shear fields, the difference between El Niño and La Niña years is consistent with expectations based on the tendency of TCs to form and maintain intensity farther poleward during La Niña years. For example, sea surface temperature appears to be an important influence on tropical cyclone activity in the central and east South Pacific in that the ENSO modulates SSTs in this region above or below the threshold of $26^\circ$C. The enhanced (reduced) low-level vorticity during El Niño (La Niña) years in the central SPO is consistent with the eastward expansion (westward contraction) of TC activity in this region. However, a vorticity gradient does not persist to latitudes of $\sim 20^\circ$S, suggesting it does not play a large role as SST or wind shear in defining the ENSO-dependent shift in the critical line defining the southerly climatological boundary of negative intensity tendency.

In general, the relative humidity fields are less consistent with expectations based on the climatological features of TC activity than seen for the other large-scale environmental parameters. They do not display as strong a latitudinal stratification as the intensity tendency and genesis fields. They are not consistent with the equatorward (poleward) shift in TC activity during El Niño (La Niña) seasons, and the region with relative humidities above 60% extends farther east into the SPO during La Niña seasons than during El Niño seasons. Relative humidity is lower during El Niño than La Niña seasons in the region of enhanced TC activity during El Niño seasons at latitudes around the date line. However, there are also some examples where the fields are consistent with expectations based on TC activity, such as increased relative humidity during La Niña.
seasons in the Coral Sea and during El Niño seasons in the far-east SPO.

Given that relative humidity is well known to be an important factor in influencing TC activity, this suggests the possibility that relative humidity in the SPO where TC activity occurs may potentially be well above any critical threshold level that would typically inhibit TC activity in a mean sense. The composites of relative humidity examined in this paper (Fig. 6) show levels above 40% throughout this region, with the exception during El Niño seasons in the Coral Sea. Some studies have examined the relative importance of these factors based on synthetic indices. Camargo et al. (2007) examined the influence of ENSO on TC activity using a genesis potential index. They found that in the SPO increased values of genesis potential mainly owe to vertical wind shear and vorticity, while decreased values of genesis potential mainly owe to relative humidity in the region from the Australian coast to the date line, and wind shear and potential intensity (a factor largely based on SSTs and convective available potential energy) in the region east of the date line.

An examination of the most favorable regions for cyclogenesis for the large-scale environmental parameters shown in Figs. 7–10 (SST, vertical shear, vorticity, and relative humidity), reveals that the most common location between all four parameters coincides well with the position of maximum observed cyclogenesis (from Fig. 6) at ~170°E during El Niño years and 160°E and slightly farther south during La Niña years. This is not altogether surprising since there is considerable interdependence between the large-scale environmental parameters examined here. For example, McBride (1995) proposed that the six parameters described by Gray (1979) relating to seasonal tropical cyclone frequency (low-level relative vorticity, Coriolis parameter, vertical shear, SST, and middle-tropospheric relative humidity) could largely be reduced to two: the monsoon trough and the region where SSTs are above 26°C. The region of maximum relative vorticity and the region of small wind shear are not independent of each other in that they could both be used as indicators of the location of the monsoon trough, with relative humidity effectively a proxy for vertical motion. Given that SSTs appear to be an important influence on tropical cyclogenesis in the central and east South Pacific, this could potentially be a region where more tropical cyclones could potentially occur in a warmer world assuming, however, there is currently a very high level of uncertainty in the influence of climate change on the monsoon trough.

In addition to the influence of the large-scale atmospheric parameters, there is a strong interrelationship between the various different TC climatological features. For example, the TC system density at a particular location is in part due to how many cyclones are transported to that location and how fast they move, which is in turn dependent on the location of favorable regions of cyclogenesis and intensification. An example of this is the maximum TC system density (Fig. 2) during La Niña years, which occurs at about 18°S, 165°E between New Caledonia and Vanuatu: there are no local maxima in any of the large-scale environmental parameters at this location, suggesting that it is more likely that this local maxima in system density can likely be attributed to a focal point in TC transport with TCs being focused toward this region both from the north as well as from the northeast. A similar feature can be seen for El Niño years at about 18°S, 160°E (i.e., the Coral Sea region of the SPO) where TCs tend to move toward this location from the north and northwest, resulting in a high system density in this region, even though the large-scale environmental parameters in the Coral Sea region generally showed unfavorable anomalies during El Niño years for TC genesis and intensification.

Based on the above results, it can be concluded that many of the features apparent in the climatologies of TC characteristics are broadly consistent with expectations based on the variability of large-scale environmental atmospheric and oceanic parameters. The degree of this consistency is found to vary depending on geographic region and also between different environmental parameters. It is also apparent that there are complex interrelationships between individual characteristics of the TC climatologies (e.g., between genesis, intensification, and transport fields) and also based on the influence of the large-scale environmental variables. The results of this study show that these interrelationships are valuable to examine when interpreting individual features of TC climatologies. For seasonal forecasting purposes, or other such modeling studies (e.g., climate or downscaled data), this last point indicates that it is important to investigate and develop multifaceted synthetic indices of predicted TC activity, rather than methodologies based on single environmental parameters over large spatial and temporal scales. The results of this study can also provide useful guidance to tune numerical models effectively and verify the simulation outputs from coupled numerical models.

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APPENDIX

Description of Formulas Used to Derive Climatologies

The vector flux of TCs is taken as the vector sum of the eastward (FE), and northward (FN) TC fluxes,

\[
FE_{ij} = \sum_{z=1}^{Z} \left[ u_z \omega_{ij}(r_z) \right] \left( \sum_{ij} \omega_{ij}(r_z) \right) (N_{st} dt)^{-1},
\]

(A1)

\[
FN_{ij} = \sum_{z=1}^{Z} \left[ v_z \omega_{ij}(r_z) \right] \left( \sum_{ij} \omega_{ij}(r_z) \right) (N_{st} dx)^{-1},
\]

(A2)

where \( Z \) is the total number of TCs contributing to the data at the \((i, j)\) grid point, \( u_z \) is the zonal component of the cyclone horizontal speed, and \( v_z \) is the corresponding meridional component; \( \omega_{ij}(r) \) is the Cressman weighting function for weighting data at grid points, \( N_{st} \) is the total number of the data sampling times in a day, and \( dx \) and \( dy \) are the east–west and north–south lengths, respectively, of the grid box centered on the \((i, j)\) grid point.

The system density (SD) is calculated as

\[
SD_{ij} = \sum_{z=1}^{Z} \left[ \omega_{ij}(r_z) \right] \left( \sum_{ij} \omega_{ij}(r_z) \right) [N_{st} A(i, j)]^{-1},
\]

(A3)

where \( A(i, j) \) is the area of the grid box centered on the \((i, j)\) grid point.

The area used for normalizing the system density is a degree latitude square, following Jones and Simmonds (1993). This unit square has an area of 12 321 km\(^2\) (111 km × 111 km), corresponding to \( A(i, j) \) in Eq. (1), leading to units of cyclones per degree latitude squared.

The mean intensity (CP) of the systems is calculated as

\[
CP_{ij} = \left\{ \sum_{z=1}^{Z} \left[ cp_z \omega_{ij}(r_z) \right] \right\} \left\{ \sum_{z=1}^{Z} \omega_{ij}(r_z) \right\}^{-1},
\]

(A4)

where \( cp_z \) is the central pressure of the \( z \)th system.

The intensity tendency (PT), or the change in intensity with time \( t \), is calculated (with units of hPa per day) as

\[
PT_{ij} = \left\{ \sum_{z=1}^{Z} \left[ (\partial cp_z/\partial t) \omega_{ij}(r_z) \right] \right\} \left\{ \sum_{z=1}^{Z} \omega_{ij}(r_z) \right\}^{-1}.
\]

(A5)


