

Interannual variability of the South Pacific Convergence Zone and implications for tropical cyclone genesis

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Abstract The interannual variability of the South Pacific Niño event), displays very peculiar behaviour where the Convergence Zone (SPCZ) and its influence on tropical cyclone (TC) genesis in the South Pacific are investigated using observations and ERA40 reanalysis over the 1979–2002 period. In austral summer, the SPCZ displays four typical structures at interannual timescales. The first three are characterized by a diagonal orientation of the SPCZ and account for 85% of the summer seasons. One is close to climatology and the other two exhibit a southward or northward departure from the SPCZ climatological position. In contrast, the fourth one, that only encompasses three austral summer seasons (the extreme 1982/1983 and 1997/1998 El Niño events and the moderate 1991/1992 El Niño

event), displays very peculiar behaviour where the SPCZ largely departs from its climatological position and is zonally oriented. Variability of the western/central Pacific equatorial sea surface temperature (SST) is shown to modulate moisture transport south of the equator, thereby strongly constraining the location of the SPCZ. The SPCZ location is also shown to strongly modulate the atmospheric circulation variability in the South Pacific with specific patterns for each class. However, independently of its wide year-to-year excursions, the SPCZ is always located with the zero relative vorticity at low levels while the maximum vorticity axis lies to the south of the SPCZ position. This coherent atmospheric organisation in the SPCZ region is shown to constrain tropical cyclogenesis to occur preferentially within 10° south of the SPCZ location as this region combines all the large-scale atmospheric conditions that favour the breeding of TCs. This analysis also reveals that cyclogenesis in the central Pacific (in the vicinity of French Polynesia) only occurs when the SPCZ displays a zonal orientation while this observation was previously attributed to El Niño years in general. Different characteristics of El Niño Southern Oscillation (ENSO)-related Pacific equatorial warming are shown to impact differently on the SPCZ position, suggesting that for regional scales, such as the South Pacific, the SPCZ classification is more appropriate than a simple ENSO index to characterize TC interannual variability. These findings suggest that forecasting the strength of El Niño through SST variations in the eastern Pacific may not be sufficient to accurately predict cyclogenesis in the South Pacific, especially east of the dateline.

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1 Introduction

The South Pacific Convergence Zone (SPCZ) is characterized by a band of high cloudiness, strong convective precipitation and low-level convergence extending from the west Pacific warm pool south-eastward towards French Polynesia (Fig.1; see review by Vincent 1994). It is the only intertropical convergence zone (ITCZ) of the southern hemisphere present all year round, although it is best developed during austral summer. It has been suggested that the summertime SPCZ consists of a zonal portion located over the western Pacific warm-pool region and a diagonal portion oriented along a northwest-southeast axis east of 170E (Vincent 1994). The climatological characteristics of its eastern portion have been thought to rely on the interactions with higher latitude depressions (Kiladis et al. 1989) and on the existence of a dry zone in the south-eastern Pacific, controlled by the presence of the Andes (Takahashi and Battisti 2007). On higher frequency time-scales (daily to weekly) the zonal dry air inflow associated with trade wind strength has been shown to control the position of the SPCZ eastern margin (Lintner and Neelin 2008). On the other hand, the climatological characteristics of its western portion is likely to be influenced by both the underlying sea surface temperature (SST) gradients and the land-ocean distribution (Kiladis et al. 1989). The western part of the SPCZ is strongly influenced by the vast monsoon system that affects the Indian Ocean and Australian region, with monsoon winds extending eastward until the dateline in the SPCZ region (Fig. 1).

The SPCZ plays a significant role in global climate and is one of the major features of the southern hemisphere climate (Kiladis et al. 1989, Vincent 1994). Because the gradients of precipitation in the vicinity of the SPCZ are very strong, small displacements in its mean position can imply drastic changes in precipitation regimes for islands in the region (Gouriou and Delcroix 2002). Its location not only strongly constrains the hydrological cycle but is also the breeding ground of tropical cyclones (TCs) in the South Pacific. Despite the SPCZ's significance to tropical climate, its characteristics, dynamics and variability have attracted relatively little attention. The interannual variability of the SPCZ location and TC activity in the Australian/western Pacific have been investigated mainly with respect to their relationship with El Niño/Southern Oscillation (ENSO). It has been shown that El Niño (La Niña) events tend to occur accordingly with a north-eastward (south-westward) displacement of the SPCZ (Trenberth and Goulet 1986, Hastings 1990, Basher and Zheng 1995, Kuleshov et al. 2008), while decreasing (increasing) TC activity near Australia (Nicholls 1985, Holland et al. 1988, et al. 1989) and on the existence of a dry zone in the south-eastern Pacific, controlled by the presence of the Andes (Takahashi and Battisti 2007). On higher frequency time-scales (daily to weekly) the zonal dry air inflow associated with trade wind strength has been shown to control the position of the SPCZ eastern margin (Lintner and Neelin 2008). On the other hand, the climatological characteristics of its western portion is likely to be influenced by both the underlying sea surface temperature (SST) gradients and the land-ocean distribution (Kiladis et al. 1989). The western part of the SPCZ is strongly influenced by the vast monsoon system that affects the Indian Ocean and Australian region, with monsoon winds extending eastward until the dateline in the SPCZ region (Fig. 1).

In addition, the location of the maximum equatorial warming has been also shown to strongly modulate the atmospheric teleconnections (Ashok et al. 2007, Trenberth and Smith 2006) and to have different impacts on cyclonic activity in the Atlantic basin (Kim et al. 2009). Evidently, El Niño strength classification is subjective and is usually based on simple indices such as the southern oscillation

Fig. 1 Indo-Pacific climatology of December–January–February (DJF) precipitation (GPCP). Convergence zone positions are shown as arrows are a few streamlines extracted from the ERA40 DJF-mean surface winds in the region; we outline the vast monsoon system affecting the Indian Ocean, Australia and western part of the SPCZ (ITCZ), South Pacific Convergence Zone (SPCZ), South Indian Convergence Zone (SICZ). Dark red

Table 1 SPCZ mean latitude in its central region and mean slope (as averaged latitude and slope of the SPCZ of each reanalysis to GPCP determined from a linear fit to the SPCZ position). Standard deviation on the 1979–2002 DJF seasons of the latitude of the SPCZ in its central region. Correlations of the

	GPCP	CMAP	ERA40	NCEP1	NCEP2
SPCZ mean latitude in 160°E–140°W (°S)	12.2	11.9	11.3	12.5	12.3
SPCZ mean slope (°/E)	0.27	0.26	0.2	0.14	0.17
SPCZ standard deviation (in 160°E–140°W)	3.2	3.1	2.3	1.6	2.4
Correlation with GPCP of					
Lat of the SPCZ (160°E–140°W)	1	0.98	0.89	0.83	0.79
Slope of the SPCZ	1	0.81	0.75	0.17	0.54

defined as the area where DJF mean precipitation is higher than 6 mm/day. Points where precipitation is lower than this threshold are not included in the SPCZ line.

2.2 Choice of the reanalysis

We rely on atmospheric reanalysis products to describe the dynamical structure of the SPCZ as they are available over extended periods (from at least 1979) and provide a dynamically consistent view of the large-scale convergence zone and its variability.

The climatological characteristics of the SPCZ location given by the precipitation fields of the two reanalyses (NCEP1 and NCEP2 from NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) and by the reanalysis ERA40 from ECMWF (European Center for Medium-range Weather Forecasts)) are displayed in Fig. 2b and summarized in Table 1. The mean latitude of the SPCZ in its central region is found to be close to the observed one for all reanalyses. All reanalysis products, however, underestimate the SPCZ slope determined from satellite data (Table 1). This zonal bias is less pronounced in ERA40 compared to NCEP1 and NCEP2, and NCEP1 and NCEP2 display a spurious double-ITCZ pattern in the eastern Pacific, especially in 1983/1984, 1984/1985, 1987/1988, 1998/1999 (not shown).

The interannual meridional displacement of the SPCZ in these datasets is compared to GPCP by correlating its zonal position (mean latitude between 160°E and 140°W (Table 1)). CMAP and GPCP display very coherent temporal variability in phase and amplitude. In comparison, all reanalysis products underestimate the amplitude of the SPCZ position interannual variability by about 30% (Table 1). However, the variability of the SPCZ position and slope is better reproduced in ERA40 than in NCEP reanalyses (Table 1). Based on these findings, ERA40 is chosen in the following to illustrate the dynamical organisation of the SPCZ (part 3.3). The period used for the whole study will span the years 1979–2002 as it is the common period of precipitation observations and ERA40 availability.

3.1 Precipitation variability in the Southwest Pacific

The main modes of interannual variability affecting the SPCZ are extracted by applying a rotated Empirical Orthogonal Function analysis (using the varimax method described in Reymond and Rotunno 1993) to the austral summer precipitation in the South Pacific region (135°E–160°W/0°–30°S).¹ Results are shown for GPCP in Fig. 3.

Very similar modes are obtained using CMAP or ERA40 as illustrated by the high correlation of their first two principal components (PCs) to GPCP (Table 2). The first and second EOFs represent, respectively, 52 and 17% of the total variance in observations (with all other modes lower than 7%). Both EOF1 and EOF2 display opposite variability on each side of the mean SPCZ position with largest amplitude, respectively, in the western and eastern parts of the SPCZ (Fig. 3c). As seen in Fig. 3c, most years only project onto the first EOF, implying that the precipitation variability is mostly characterised by a north-south movement of the SPCZ in the 160°E–140°W region. Three years only (1982/1983, 1991/1992 and 1997/1998) have positive contributions to both PC1 and PC2. The resulting precipitation pattern is characterized by strong positive precipitation anomalies extending throughout the equatorial Pacific. This EOF analysis therefore reveals that the interannual variability of the SPCZ position differs in its western and eastern portions (described, respectively, by EOF1 and EOF2). To specify the longitude of the transition between these western and eastern behaviours, an EOF analysis on the latitude of the SPCZ at each longitude is performed. It displays a first mode characterising the north-south displacement of the SPCZ and a second mode opposing the variability of the SPCZ location east and west of 175°W (not shown). Describing the SPCZ movement using a single index will hence mainly capture the vari-

The same analysis performed with the eastern boundary at 120°E and 140°W yields very similar results.

Fig. 3 a, b First and second EOFs of GPCP DJF precipitation on the period 1979–2002, the thick purple line indicates the mean position of the SPCZ, and coordinates of each year on these two first modes (colors show the class to which each season belongs, see Fig. 4); year n stands for the DJF season Dec. year to Feb. year $n + 1$

Table 2 Percent variance of the two first EOFs for ERA40 reanalysis and observations, correlation of the two first PCs coordinates with respect to GPCP ones

	GPCP	CMAP	ERA40
EOF1 (% variance)	52	53.6	53.5
EOF2 (% variance)	17.2	15	15.6
PC1 correlation	1	0.97	0.97
PC2 correlation	1	0.96	0.92

All correlations significant at the 95% level with respect to a two-tailed Student's test

ability related to the first EOF. To account for the information contained in both first and second EOFs, we describe the SPCZ latitude averaged between 160 and 180 and latE is the SPCZ latitude averaged between 170 and 150 W).

A classification using an ascendant hierarchical clustering (AHC; Ward 1963) method applied to these two variables (latW and latE) is then used to summarize the interannual variability of the SPCZ position. The AHC computes a hierarchical clustering of SPCZ characteristics for the 23 austral summer seasons considered in the analysis. At the first step, there are 23 clusters; then, at each step, the two closest clusters are aggregated according to the Ward criterion with Euclidean distances as the dissimilarity measure. This method ensures a classification in which the elements of a given cluster are as close as possible to each other and as far as possible to elements of other clusters. The resulting dendrogram (or classification tree) shown on Fig. 4a depicts the partitioning from 23

clusters at the bottom of the tree to a unique cluster at the top of it. Each leaf of the tree is a subset of the 23 seasons with each node represents the conjunction of two clusters, the height of its branch being representative of the distance between two clusters. The last important jump of inter-

cluster distance as the number of classes increases is seen for a division into four clusters (Fig. 4b). Seasons associated to each of these four classes are highlighted by different colours in Figs 3c and 4a. Clusters determined by this method do also show up in the PC1–PC2 plane (Fig. 3c) thereby giving confidence that our classification is robust. This observation also confirms that the SPCZ location (on which the classification is performed) accurately summarizes the large-scale precipitation variability in the tropical South Pacific (on which the EOFs are constructed). The same AHC applied to PC1–PC2 coordinates instead of latW–latE indices gives indeed similar clusters. In the following, we will refer to the classification based on latW–latE indices that are, by construction, more representative of the SPCZ location than the EOF analysis (as the EOF analysis also accounts for variations in precipitation intensity within the SPCZ and at the equator). This classification is stable when using CMAP or ERA40 datasets, as well as when the boundaries of the western and eastern boxes are slightly changed.

The SPCZ location for each of the 4 classes is displayed on Fig. 5a. The “negative”, “neutral” and “positive” classes are similar to the composites described in Folland et al. (2002). Within these classes, the SPCZ location is shifted in latitude with little change in its slope. In contrast, the “asymmetric” class has never been investigated in detail and is characterized by the SPCZ becoming almost zonal from 150E to 140W and merging with the ITCZ that is no longer observed in the North Pacific, west of 160W (not shown). The corresponding cluster contains only three seasons (1982/1983, 1991/1992, 1997/1998) and its specificity will be discussed in detail in the following section.

Changes in the position of the SPCZ are also associated with modifications of total precipitation fluxes in the SPCZ region. As seen on Fig. 5b, there is a clear increase of the total precipitation flux from “neutral” to “positive” and “asymmetric” years with 50% more precipitation during

Fig. 4 a Dendrogram resulting from the ascending hierarchical classification (AHC) performed on the two variables: latW and latE. b Inter-cluster distance (in the centred and normalized space of coordinates on the two variables) as a function of the number of classes. Red dashed line indicates the cutting level; four clusters are identified

Fig. 5 a Positions of the SPCZ from GPCP for each class: asymmetric (orange), positive (black), neutral (red) and negative (blue) years. Total precipitation flux (in Sverdrup) in the SPCZ region (14E–120 W/0E–30S)

the latter with respect to neutral conditions, while asymmetric and negative years show little difference from the neutral case. The increase of total precipitation is mainly due to the greater extension of the precipitating area (the SPCZ region) rather than an intensification of it. Indeed the area receiving a flux >6 mm/day shows a similar 50% increase between asymmetric and neutral years while the precipitation rate within the SPCZ varies by 10% between classes.

3.2 SST forcing of SPCZ interannual variability

In the previous section, a description of the SPCZ interannual variability has been conducted outside of any consideration of ENSO. In this section, we investigate the relation to ENSO and associated SST forcing of SPCZ displacements.

The high value of the correlation coefficients between the SPCZ latitude and the Niño 3 or Niño 3.4 index (Table 3) confirms that SPCZ interannual variability is primarily related to ENSO. However, the SPCZ position in northward (southward) displacement of the SPCZ latW is not as well correlated with the classical Niño indices (Niño 3 and Niño 3.4) as in latE (Table 3), mainly because the three asymmetric events strongly degrade the correlation. Indeed, in contrast to the neutral northward tendency, the SPCZ in latW moves toward the south for these years and is found around 8° (Figs. 5a, 6a) contributing to the zonal orientation of the SPCZ. When

Table 3. DJF correlation coefficients between Niño 3.4 and Niño 3.4 indices (HadISST) and SPCZ position proxies: latW and latE (GPCP); the fourth and fifth rows present the correlations of SPCZ latitude with SST indices that were found to yield the highest correlations (in bold in the table, see text) with the SPCZ indices in latW and latE, respectively

corr coef	latW	latE
Niño 3	0.56	0.81
Niño 3.4	0.71	0.83
Niño 4	0.84	0.70
SST in 170E–170W/5 N–5S	0.87	0.60
Warm Pool eastern margin	0.64	0.92

All correlations significant at the 95% level with respect to a two-tailed Student's test

discarding these three years from the calculation, the correlation between latW and Niño 3 (Niño 3.4) SST increases to 0.74 (0.81). In agreement with Folland et al. (2002), El Niño years are generally found to drive a northward (southward) displacement of the SPCZ latW. However, SPCZ displacements during El Niño events are more diverse than previously thought: El Niño events separate into two distinct clusters, displaying either a northward shift or a zonal alignment of the SPCZ position. In addition, this relationship is not systematic: three neutral ENSO years display a northward excursion of the SPCZ (1992/1993, 1989/1990 and 2001/2002), which is usually

Fig. 6 Scatter plot of DJF latitude of the SPCZ in latW versus SST anomalies in the 170°E–170°W/5°N–5°S region and in latE versus easternmost extension of the Warm Pool at the equator (as marked by the 29°C SST isotherm in HadISST dataset). These two SST indices are chosen as they are the ones that yield the highest correlations with latW and latE indexes

Table 4 Comparison of years belonging to the classes formed by the classification on SPCZ position (left) and on the index (right)

SPCZ position classification	ENSO classification
Asymmetric years 1982/1983, 1991/1992, 1997/1998	-0 years 1982/1983, 1997/1998, 1991/1992, 1986/1987, 1994/1995, 1987/1988, 1979/1980
Positive years 1992/1993, 1986/1987, 1994/1995, 2001/2002, 1987/1988, 1989/1990, 1979/1980	Neutral ENSO years 1992/1993, 1990/1991, 1989/1990, 1993/1994, 1981/1982, 2001/2002, 1980/1981, 1996/1997, 1985/1986
Neutral years 1980/1981, 1984/1985, 1990/1991, 1996/1997, 1985/1986, 1981/1982, 1993/1994	+a years 1995/1996, 1983/1984, 2000/2001, 1984/1985, 1998/1999, 1999/2000, 1988/1989
Negative years 1995/1996, 1998/1999, 2000/2001, 1999/2000, 1983/1984, 1988/1989	

Years are ordered by the amplitude of the mean SPCZ displacement (left) and by the amplitude of SST anomaly (right)

The monthly temperature averaged over the Niño 3.4 region (5°S–5°N, 170°W–120°W) is used to characterize the El Niño/La Niña phenomenon. El Niño (La Niña) years are defined as those when the DJF Niño 3.4 SST anomaly is greater than (lower than) 1°C as defined by NOAA in http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml

typical of El Niño years, while one La Niña event (1984/1985) corresponds to a neutral SPCZ season, with the SPCZ close to the climatological position (Table 4).

LatW and latE are both strongly correlated to the equatorial SST variability but the location of SST with the two indices. While for latW the strongest correlations are found around the dateline (170°E–170°W/5°N–5°S; Table 3; Fig. 6a), latE displays the strongest positive correlations with SSTs in the central Pacific (170°W–120°W/5°N–5°S, i.e., Niño 3.4 region; see Table 3). This latter region experiences large fluctuations of the eastern edge of the warm pool during the ENSO cycle. The eastern edge of the warm pool at the equator (here defined by the longitude of the 29°C isotherm) arises as a better predictor of eastern SPCZ latitude (latE) than Niño 3 or Niño 3.4 indices (Table 3; Fig. 6b).

In Fig. 7c, we note that the SPCZ is located over a large area of warm water extending from the warm pool south-eastward into the South Pacific. Associated with SPCZ variability, the SST pattern is deeply modified (Fig. 7a, b, d). SST anomalies have two major impacts of interest in the definition of the SPCZ: they drive surface wind anomalies, and they modulate the amount of humidity available in the lower layers of the troposphere. Because tropical convective regions are primarily forced by moisture convergence, analysing the changes in wind patterns and moisture convergence in relation to the SPCZ variability allow us to better understand the mechanism of SST forcings driving the variations of SPCZ location. For the positive cluster, the slight eastward shift of the warm pool eastern boundary results in maximum SST anomalies around 160°W driving low level wind anomalies in the western Pacific west of 160°W that are maximum just

Fig. 7 Sea surface temperature (*SST*) for c the “neutral” class and a, b, d *SST* anomalies with respect to the “neutral” class of the “asymmetric”, “positive”, and “negative” classes, respectively. *Black arrows* are winds on the 850 hPa level in (b) and anomalies from the “neutral” winds on other panels

Fig. 8 Moisture divergence at 850 hPa $\nabla \cdot \vec{v}$ (in $\text{g kg}^{-1} \text{day}^{-1}$; with q specific humidity and \vec{v} winds from ERA40 on the 850 hPa level) for c the “neutral” class, and b, d moisture divergence anomalies with respect to the “neutral” class of the “asymmetric”, “positive”, and “negative” classes, respectively. The *red line* is the 29 C isotherm, *purple line* is the SPCZ position, *red dashed line* is the maximum *SST* axis, the *thick dashed black line* points the maximum moisture convergence location and *black arrows* are winds on the 850 hPa level in (b) and anomalies from the “neutral” winds on other panels

south of the equator (Fig. 7b). This southward shift of the north of the mean SPCZ position, displacing the maximum wind response to the equatorially centred *SST* anomalies in moisture convergence and precipitation axis about 3 a robust feature of El Niño years in austral summer (Larkin and Harrison 2002) and has been suggested to be fundamentally tied to the annual cycle of insolation through the peculiar non-linear response of convective anomalies to the warmest *SST* migrating south of the equator during austral summer (Spencer 2004; Harrison and Vecchi 1999; Harrison et al. 2006). This wind pattern acts to slightly increase wind convergence just north of the mean SPCZ northward shift of the maximum moisture convergence and

Pacific *SST* anomalies. The eastern Pacific warming a subsequent SPCZ shift of about 10° to the north (Fig. 8b). A similar argument may explain the SPCZ displacement by the 1982/1983 and 1997/1998 events, however, the the “negative” class. In this case, the westward shift of the maximum is found between 170°E and 150°W, Fig. 7d) three seasons display the largest eastward extension of the generates wind anomalies that increase the divergence of a warm pool, reaching longitudes east of 160° (Fig. 6b).

Compared to the "positive" cluster, this larger warm pool precipitation (see Fig. 3). The first mode (39% of the total expansion of the "asymmetric" cluster results in variance) opposes regions north and south of the mean stronger and eastward-shifted low-level wind anomalies maximum vorticity axis west of 160°W (Fig. 9a), while the which are maximum east of the dateline, just south of the second mode (13% of the total variance) displays a strong equator (Fig. 8a). These anomalies increase considerably cyclonic anomaly east of 170°W (Fig. 9b). The PC1 and PC2 the moisture convergence in this region, allowing a distribution is also similar to the precipitation one (com- placement of the maximum moisture convergence and precipitation axis of about 10° to the north.

West of the dateline, the SPCZ is not shifted northward three "asymmetric" events. The interannual variability of as in the "positive" cluster but remains close to its mean level vorticity is therefore intimately tied to precipi- position. During "asymmetric" events, a cold SST anomaly variability in the South Pacific (correlation of PC1s maly is observed in the north-west Pacific (Fig. 7). This from precipitation and vorticity is 0.95). The same analysis leads to decreased humidity levels and a strong divergence applied to the surface wind, the surface wind divergence or anomaly that together generate a net divergence of 600 hPa vertical velocity gives very similar results (not humidity in the north-western ITCZ and around the equator shown), suggesting more generally that the dynamical (Fig. 8a), inhibiting precipitation and preventing a north- fields are strongly tied to the SPCZ variability in this ward shift of the SPCZ west of the dateline. region.

The zonal orientation of the SPCZ therefore occurs. Figure 10 displays the surface wind patterns in the when the warm pool also presents a zonal shape being South Pacific for each of the four classes arising from the moved southward in the west and eastward around the SPCZ classification. We begin with the "neutral" class, as it equator due to the disappearance of the equatorial presents a wind structure close to the climatological one in upwelling in the central part of the basin. During "asym- the South Pacific (Fig. 10c). Convective precipitation in metric" events, the maximum SST axis is zonally oriented the SPCZ region is essentially tied to surface wind con- and the maximum precipitation is collocated with it. In the vergence. This convergence arises from the confluence of other clusters, the western portion of the SPCZ is anchored the trade winds in the eastern SPCZ, while, in its western to the warmest water while the SPCZ is located slightly part, it results from the convergence of Australian monsoon poleward of this axis of maximum SST in its eastern end winds (north of the SPCZ) and the trade winds (south of it). (and on its full length in the "negative" class), Fig. 11. The transition between these two different dynamical finding supports the idea that the SPCZ is mainly con- regimes within the SPCZ is represented by the confluence trolled by SST forcing when it is close to the equator, but point (CP), defined as the easternmost point at any latitude also to some extent by interactions with the extra-tropical reached by monsoon westerlies in the South Pacific circulation when it is positioned further from the equator (adapting the original definition that Chan and Evans (Kiladis et al. 1989). (2002) used in the Northwest Pacific ITCZ). Interestingly,

Previous studies have shown the importance of distin- the CP defined in this way is, for all DJF seasons, located guishing Niño extremes from other events as they have on the SPCZ line. The monsoon trough, defined as the different physical lifecycles (Lengaigne and Vecchi 2009) region of minimum surface pressure, is characterised by and yield different impacts on TC activity (Kim et al. 2009). Here we confirm these studies by showing that moist, southwest monsoon flows on its equatorward side and easterly trades on its poleward side (2004). Within the monsoon trough region is found the monsoon differently on the SPCZ position. However, the moderateshear line (MSL) where the maximum cyclonic vorticity is strength El Niño of 1991/1992 appears in our classification found as the encounter between the eastward monsoon at the side of the two strongest El Niño events illustrating winds and westward trade winds results in strong meridi- the need to define local indices for regional studies rather than apply a general ENSO index. zonal wind shear. East of the CP, cyclonic vorticity is associated with curving trade winds and is weaker: the CP longitude thus marks the eastern boundary of the MSL. The CP also appears to be a good proxy for the strength of the MSL since the intensity of the vorticity averaged along the axis of the MSL is strongly correlated with the CP longi- tude (0.89). In contrast to the north-west Pacific ITCZ where the maximum cyclonic vorticity is found to be col- located with the maximum of precipitation and as been used to define the ITCZ axis (Chan and Evans 2002), the maximum cyclonic vorticity in the SPCZ lies 6° south of

3.3 Relationship between surface wind and SPCZ variability

The SPCZ location is not only strongly associated with large-scale precipitation, SST and moisture convergence but also with the dynamical fields. This is illustrated in Fig. 9 by applying a rotated EOF analysis to the surface wind curl (low-level vorticity), in a similar way as for the

Fig. 9 a, b First two EOFs of ERA40 DJF vorticity on the period 1979–2002, and coordinates of each year on the two-prst modes. Colors remind the class to which each season belongs, see Sect. 1 and Fig. 4). The dashed line marks the mean maximum vorticity axis

the maximum precipitation that is collocated with the zero provides a first look at the interannual variability of the of the vorticity field (Table 5; Fig. 10). This dynamical genesis location in the South Pacific (Fig. 11). It appears organisation described from climatological fields is also that the 3 years forming the SPCZ “asymmetric” cluster valid in interannual variations. The displacement of the defined in the previous section are neatly separated from zero and maximum vorticity axes are strongly tied to the the rest as their mean longitude of genesis is located east of interannual evolution of the SPCZ on its western and the dateline. In addition, “negative” years display a more eastern part (Table 5) showing that the MSL variability is southern location in their mean genesis latitude than do the closely related to the SPCZ variability. From “negative” the years. In contrast, no clear difference in the mean “asymmetric”, the MSL increases in strength while the genesis location is observed between “neutral” and is displaced north-eastward. During “asymmetric” years, positive” years with regard to their mean genesis position. the SPCZ is almost entirely defined by a monsoon type This first observation is extended by analysing com- convergence zone, and low-level vorticity within the posites of genesis density maps of the Southern Hemi- monsoon trough increases considerably east of the dateline. sphere cyclonic seasons (July year n to June year $n + 1$). (Fig. 10a).

4 Importance of the position of the SPCZ for tropical cyclogenesis

In the previous section, surface wind variability has been associated standard deviation in zonal and meridional shown to be strongly connected to the displacement of the directions, respectively, of 1.5 and 3 following the SPCZ. TC genesis is known to be dependent on large scale method used by Ramsay et al. (2008). Each genesis point is dynamical and thermodynamical fields and surface cyclospatially extended following this Gaussian shape and nic vorticity is one of the variables that favour the genesis density maps for each cyclonic season are obtained by of TCs (Gray 1979). In this section, we will investigate the summing the contribution of each Gaussian on a relationship between the interannual variability of the 2.5×2.5 grid. On average, the TC genesis distribution is SPCZ and the interannual variability of TC genesis almost zonal (between 10° and 15°S) and extends from the northern coast of Australia to 160°W (Fig. 12c). For each SPCZ class, the genesis region (black dashed line) is located just south of the SPCZ position. “Asymmetric” and “positive” years both display increased cyclogenesis in the Tuvalu region and decreased cyclogenesis in the Coral Sea. Opposite variations are found for “negative” years in these regions. If the genesis patterns are similar west of the dateline for the “positive” and “asymmetric” classes, they strongly differ east of it. A large positive anomaly of

4.1 TC genesis variability in the South Pacific

The mean position of TC genesis for each season derived from the Joint Typhoon Warning Center (JTWC) dataset² is shown in Fig. 12a. Genesis is defined as the first position of a Tropical Depression in the JTWC database that will develop 1-min averaged winds of 17 m/s.

Fig. 10 Composite DJF surface fields related to the SPCZ for the magnitude of the vorticity along the monsoon shear line (MSL); red four classes: a) asymmetric positive, b) neutral, c) and d) negative class. The line is the SPCZ composite position; the confluence point (CP) defined as the point of the SPCZ where blue vectors represent the surface wind field; region of cyclonic relative vorticity of surface winds shaded in grey, the blue line points the maximum vorticity axis and its thickness represents the

cyclogenesis in the central Pacific (Polynesia region), is the SPCZ (not shown). The CSGP is also able to reproduce indeed observed during asymmetric years and contrast the broad features of genesis anomaly patterns associated with the weak anomaly found in the positive class (Fig. 12b).

4.2 Interannual variability of TC genesis favourable parameters

Tropical cyclones have a tendency to form in regions with negative anomaly of genesis in the Coral Sea for the two favourable large-scale environmental parameters: high oceanic heat content (OHC), low-level cyclonic vorticity, sufficient intensity (and neither by SGP and GPI). Here we build on the terms involved in the calculation of the CSGP to understand the link observed between TC indices and SPCZ position interannually. Three terms are involved in the CSGP calculation: the dynamic potential, the vertical shear of winds between 950 and 200 hPa, and the potential index (SGP) followed by Emanuel and Nolan (2004) who developed another genesis potential index (GPI). Both indices are constructed as an empirical combination of all favourable variables fitted to the observed numbers of genesis globally. Royer et al. (1998) simplified these three terms calculation). In the neutral years the thermal potential of the SGP index by considering only minimum vertical shear (shear < 16 m s⁻¹/750 hPa) is runs of general circulation models) and named it the convective seasonal genesis potential index (CSGP, see Appendix). Compared to the GPI and SGP, the CSGP was found to best reproduce both the climatological pattern and the interannual variations of TC genesis in the South Pacific (Menkes et al. 2009). In particular, it is almost able to reproduce the observed location of maximum cyclogenesis to the south of the SPCZ (Fig. 13c) while other indices locate the maximum of genesis right on the neutral class is also valid for the three other

Table 5 Mean distance and correlation between the zero and maximum vorticity axes to the SPCZ position in latW and latE regions

	In lat W	In lat E
SPCZ and zero vorticity axis		
Mean distance (lat)	0.7	-0.6
Correlation	0.93	0.91
SPCZ and max vorticity axis (MSL)		
Mean distance (lat)	-5.7	-6.2
Correlation	0.88	0.82

All correlations significant at the 95% level with respect to a two-tailed Student's test

composites (Fig. 14a, b, d). Figure 14 shows that the overlap area of positive vorticity, shear values lower than $9 \text{ m s}^{-1}/750 \text{ hPa}$ and convective precipitation 4 mm/day is always found just south of the SPCZ position and west of the CP. The region of observed TC genesis (thick black dashed line) is shown to match this overlap region, with 67% of observed TCs in the South Pacific forming inside this region. The proportion increases to 87% when considering the $16 \text{ m s}^{-1}/750 \text{ hPa}$ vertical shear instead of the $9 \text{ m s}^{-1}/750 \text{ hPa}$. Chand and Walsh (2009) note that TC genesis over the Fiji region is highly favoured for environmental vertical wind shear 8 m/s compares to our value of 9 m/s (calculated between 950 and 200 hPa levels) even if our calculation is based on DJF means while their calculation is based on daily composites.

The regions of greater variability for cyclogenesis in different SPCZ classes are identified in Fig. 10. These are the Polynesia ($165^{\circ}\text{W}/5^{\circ}\text{S}$ to $130^{\circ}\text{W}/20^{\circ}\text{S}$), Tuvalu ($165^{\circ}\text{E}/165^{\circ}\text{W}/5^{\circ}\text{S}$ to $135^{\circ}\text{E}/13^{\circ}\text{S}$), Fiji ($165^{\circ}\text{W}/13^{\circ}\text{S}$ to $145^{\circ}\text{E}/10^{\circ}\text{S}$) and Coral Sea ($145^{\circ}\text{E}/13^{\circ}\text{S}$ to $120^{\circ}\text{E}/20^{\circ}\text{S}$) regions. To identify the large scale parameters associated with cyclogenesis variability, we compare the TC genesis number per region with the CSGP and the three terms composing it averaged over each of the four regions (Fig. 15). The latter three terms are normalised by their mean magnitude over the South Pacific domain ($145^{\circ}\text{E}/120^{\circ}\text{W}/0^{\circ}\text{S}$ to 130°S) to allow for comparison both between terms and between regions. We first note that the Polynesia region is affected

cyclogenesis only during the three asymmetric years. This observation is reasonably well reproduced by the CSGP and main variability appears to be due to the vorticity and thermal potential terms (Fig. 5). The zonal orientation of the SPCZ during asymmetric years brings deep convection to the central Pacific and allows the eastward extension of background cyclonic vorticity in the Polynesia region (Fig. 14).

In the Tuvalu region, no cyclones are formed during negative years despite favourable shear and thermodynamical conditions. In this case, the background anti-cyclonic vorticity due to the southward SPCZ shift has produced locally unfavourable conditions responsible for this absence of genesis (Fig. 5). From neutral to asymmetric years, an increase of TC genesis number is observed; the CSGP catches an increase of favourable conditions but overestimates the observed variability for the positive and asymmetric classes. All CSGP terms vary accordingly with the observed increase of cyclogenesis but the vorticity term appears to be the primary driver of the CSGP increase for the positive and asymmetric classes. We remark that the 1996/1997 season is outside of the neutral group with regards to TC genesis number and degrades the relationship (Fig. 5a). During this year, TCs are formed late in the season (2 in March, 2 in April, 1 in May and 1 in June 1997). These late geneses with respect to a standard season are probably related to the onset of the strong El Niño event in March 1997 and are responsible for the peculiar behaviour of this cyclonic season.

In the Coral Sea region, vorticity is always favourable for TC genesis. Indeed the region lies at the heart of the monsoon trough eastern portion that experiences a persistent horizontal shear between monsoon and trade winds. The genesis density difference between negative, neutral and positive asymmetric observed in Fig. 12 seems to be mostly sensitive to the thermodynamical potential that shows the greatest relative modification. However, little confidence can be given to this result as all three indices show poor skill in reproducing the interannual variability of TC genesis in this region.

Fig. 11 Mean position of cyclogenesis for each year in the South Pacific region (145°E to $120^{\circ}\text{W}/0^{\circ}$ to 30°S): year n stands for the Southern Hemisphere cyclonic season from July year n to June year $n + 1$. Overall mean longitude and latitude given by the dashed lines

Fig. 12 Neutral class TC genesis density (in number of genesis neutral case; the dashed contour is the isoline four TC/ per 20 years and per 5 × 5 boxes); rectangles delimitate the 20 years/(5 × 5) of TC genesis density. Climatological GPCP different regions discussed in the text: Coral Sea, 2 Tuvalu, 3 Fiji SPCZ (green dashed line) and composite SPCZ (green line) are and 4 Polynesia. a Asymmetric, b positive, c negative reported on each map composites of TC genesis density anomaly with respect to the

Fig. 13 Same as Fig12 but for the composites of the convective composites of genesis density anomaly with respect to the Neutral seasonal genesis potential index (GP) for the four classes. Units of case; the thick dashed contour is the four TC/20 years/(5 × 5) the index are fitted to the global TC number and can be read as composite isoline. Climatological ERA40 SPCZ (green dashed line) formation of TC per 5 lonlat boxes per 20 year. Neutral class and composite SPCZ (green line) are reported on each map genesis density. a Asymmetric, b positive, c negative years

In the Fiji region, vorticity is also always favourable. Summary and conclusions and even if increasing from negative to asymmetric years, the genesis of TCs follows an inverse tendency. This study investigates the interannual variability of the which is to be related to the thermal potential (and to a SPCZ and its influence on TC genesis using satellite data lesser extent to wind shear) which decreases from negative ERA40 reanalysis over the 1979–2002 period. tive to asymmetric years. We remark that An AHC method allows four characteristic structures of relatively to other regions, the CSGP always tends to the interannual position of the SPCZ in austral summer to overestimate the number of genesis in Fiji and Tonga. A neutral class gathers years when the Sea regions. SPCZ is close to the climatological position, while a Conducting a similar analysis on the different terms negative (positive) class gathers years when the SPCZ composing the GPI of Emanuel and Nolan (2004) yields is displaced by about 3 south (north) of its climatological very similar results (not shown) about the relative importance of dynamical and thermodynamical terms to the orientation of the SPCZ position. In contrast, the fourth strain the interannual variability of cyclogenesis. class (the asymmetric class), that only contains 3 years

Fig. 14 Composites of ERA40 terms involved in the calculation of the CSGP: *green* 9 and 16 m s⁻¹/750 hPa contours of vertical wind shear (between 950 and 200 hPa); *blue* 0 s⁻¹ contour of surface relative vorticity and *purple* 4 mm/day contour of convective precipitation; *purple line* SPCZ composite position and the thick dashed contour reproduces the four TC/20 years⁻¹ line of TC genesis density of Fig. 12

Fig. 15 a Averaged TC genesis number and value reconstructed from the CSGP per region and per class [from left to right: "negative" (*blue*), "neutral" (*black*), "positive" (*red*) and "asymmetric" (*red*)] and comparison with the terms involved in the calculation of the CSGP (non-dimensional units): vorticity term I_v , wind shear term I_s and thermodynamical term I_{pot} . Each term is normalised by its average magnitude in the South Pacific domain (10°S–20°S, 120°W–180°E) to allow comparison between terms and between regions. *plus marks* the value of an individual year forming the class for an evaluation of its homogeneity

(the extremes 1982/1983 and 1997/1998 El Niño events and the moderate 1991/1992 El Niño event) displays an SPCZ that is zonally oriented located around 5°S well as during the moderate 1991/1992 El Niño when the eastern edge of the equatorial warm-pool is displaced east of 160°W. This considerably increases the moisture transport south of the equator, shifting the SPCZ location east of the dateline by more than 10° north of its climatological position. Moreover, the western part of the SPCZ (2002). More precisely, the SPCZ location east (west) of the dateline is strongly related to the variability of the equatorial SST in the central Pacific (near the dateline) suppressing the ITCZ here during "asymmetric" years while SPCZ and ITCZ are merged along the equator during "positive" years.

This study confirms that ENSO phenomenon strongly modulates the SPCZ movement, as first discussed by Trenberth (1976) and in agreement with Folland et al. (2002). More precisely, the SPCZ location east (west) of the dateline is strongly related to the variability of the equatorial SST in the central Pacific (near the dateline) suppressing the ITCZ here during "asymmetric" years while SPCZ and ITCZ are merged along the equator during "positive" years.

The SPCZ location is found to be a good indicator of the changes to atmospheric circulation in the South Pacific. From year-to-year, the SPCZ location is collocated with the zero relative vorticity axis at low levels, while the MSL

(i.e., the maximum vorticity axis) lies south of the SPCZ summer equatorial Pacific warming leads to different position. In addition, both the eastward extension of impacts on the cyclogenesis in the Atlantic basin, we here monsoon wind and the intensity of the MSL increase as the show that similar characteristics of the austral summer SPCZ is displaced northward. During "asymmetric" years, equatorial Pacific warming have to be taken into account the SPCZ can even be almost entirely defined by a monsoon when addressing the interannual variability of cyclogenesis soon type convergence regime and the vorticity increases in the south-west Pacific. This sensitivity of SPCZ variation considerably east of the dateline. Because the SPCZ positions and related cyclogenesis in the central Pacific to the tion summarizes large scale dynamic and thermodynamic equatorial warm pool extent suggests the possibility of fields, it is also shown to be a good indicator of the additional predictability of cyclogenesis in this region geography of cyclogenesis in the South Pacific. Genesis beyond that associated with just predicting the occurrence indices such as the CSGP allow to study the main factors of El Niño. However, predictions of the details of the favouring or limiting cyclogenesis. Based on analysis of pattern of the SST anomalies during El Niño have not yet these factors, we conclude that the anticyclonic vorticity of been demonstrated.

low-level winds just north of the SPCZ prevents cyclogenesis in this region while low wind shear within the troposphere, vertical instability of the troposphere (depicted as deep convective precipitations) and cyclonic vorticity of low-level wind combine just south of the SPCZ to allow TCs to develop. Cyclogenesis interannual variability in the region is shown to follow SPCZ movement in its north-south displacement and to preferentially occur within 10° south of the SPCZ location. Four distinct spatial patterns are depicted in the TC observations in relation to the SPCZ classes. These patterns are also correctly reproduced by the CSGP (but also by the GPI and SGP indices). Even if the actual TC genesis numbers cannot be reproduced by these indices due to the intrinsic high level of stochasticity in TC genesis in that region (see Jourdain et al. 2009, Menkes et al. 2009 for a detailed discussion), indices do reproduce the "asymmetric" and "negative" patterns pretty well, but do not reproduce the decrease of cyclogenesis in the Coral Sea during "positive" and "asymmetric" phases.

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Our approach provides a means of demonstrating that cyclogenesis east of the dateline (in the vicinity of French Polynesia) is only likely to occur when the SPCZ displays a zonal orientation while this observation was previously attributed to El Niño years in general. During the years of "asymmetric" SPCZ, the strong northward displacement of the SPCZ east of the dateline generates a strong positive cyclonic vorticity in this region, favouring cyclogenesis. This zonal orientation of the SPCZ and its associated increased cyclogenesis in the central Pacific depends more strongly on the west-east displacement of the eastern edge of the warm pool than on the SST anomaly magnitude depicted by the Niño 3 SST index. While the 1991/1992 El Niño is considered as a moderate El Niño based on the Niño 3 SST index, our results show that its SPCZ evolution behaves similarly to the extreme 1982/1983 and 1997/1998 El Niño events because these three events display the largest SST anomalies east of the dateline and hence the largest eastward shift of the equatorial warm pool. While Kim et al. (2009) show that the characteristics of the boreal

Details on the calculation of the convective seasonal genesis parameter (Gray, 1979) to avoid the use of fixed threshold of SST, which prevented it from being used in GCM climate simulations. They suggested replacing the thermal potential with a convective potential, or directly linked to the convective precipitation of the model:

$$CSGP = \frac{1}{4} \underbrace{\bar{\zeta}_r \frac{f}{\bar{\sigma}_p}}_{\text{DynamicPot}} \underbrace{\bar{\alpha} P_c}_{\text{ConvectivePot}}$$

Here: f is the Coriolis parameter (in 10^5 m s^{-1}), $\bar{\zeta}_r = \frac{1}{4} \zeta_r \frac{f}{\bar{\sigma}_p}$ is the low level relative vorticity at 950 hPa (in 10^6 s^{-1}), $\bar{\sigma}_p = \left(\frac{\partial \sigma}{\partial p} \approx 3\right)^{-1}$ is the inverse of the vertical shear of the horizontal wind between 950 and 200 hPa, (in $\text{m s}^{-1}/750 \text{ hPa}$),

Here: f is the Coriolis parameter (in 10^5 m s^{-1}), $\bar{\zeta}_r = \frac{1}{4} \zeta_r \frac{f}{\bar{\sigma}_p}$ is the low level relative vorticity at 950 hPa (in 10^6 s^{-1}), $\bar{\sigma}_p = \left(\frac{\partial \sigma}{\partial p} \approx 3\right)^{-1}$ is the inverse of the vertical shear of the horizontal wind between 950 and 200 hPa, (in $\text{m s}^{-1}/750 \text{ hPa}$),

€ P_c is the convective precipitation term of the model,
 € k is a constant dependent on the model.

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