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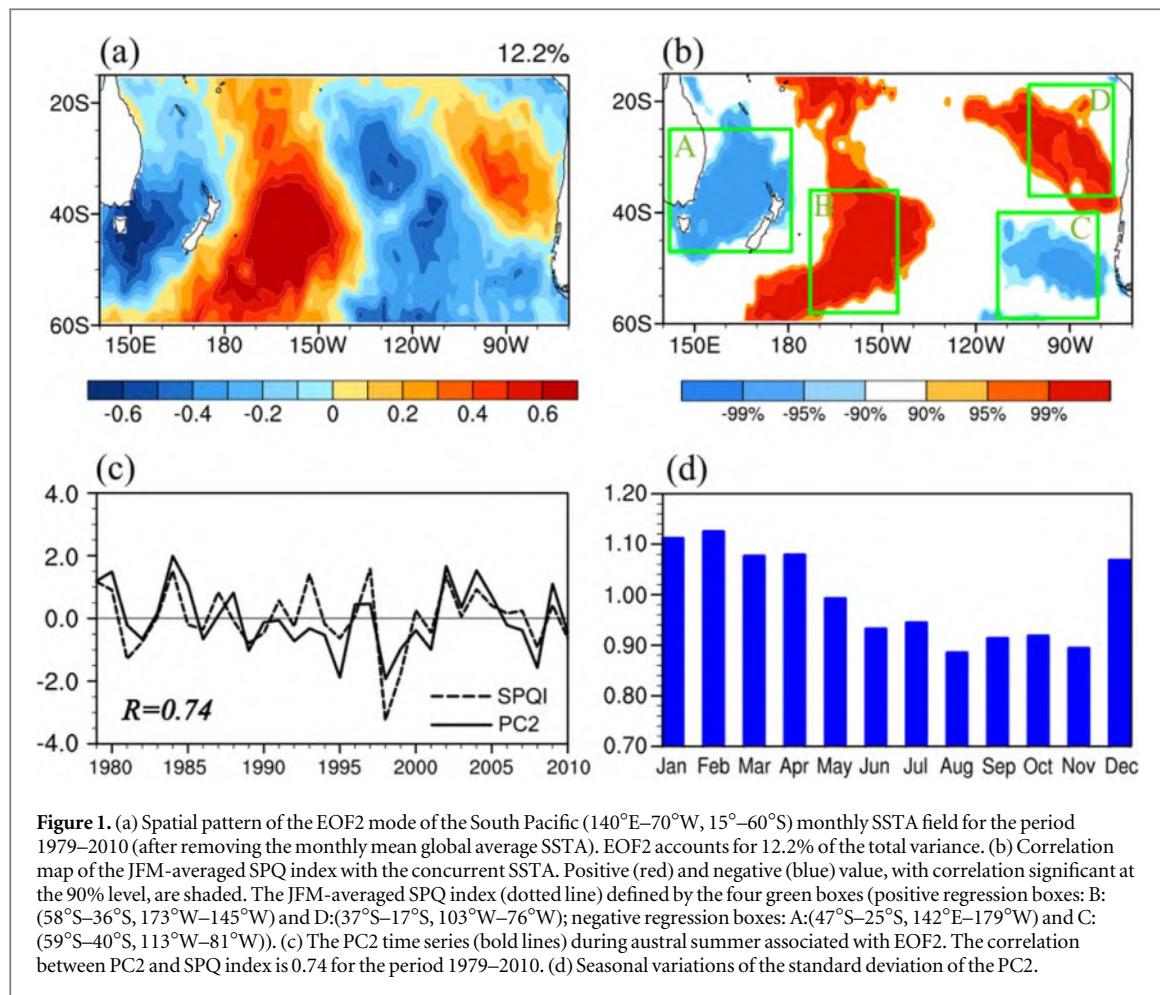
## Abstract

The South Pacific convergence zone (SPCZ) is a key component in the weather and climate system. By analogy to the intertropical convergence zone, the SPCZ is also part of the 'engine' for the tropical convection. There have been many studies about the tropical impacts on the SPCZ. Here, we show that the SPCZ, especially the precipitation in this region, is subject to the influence of South Pacific quadrupole (SPQ) in the subtropics via the mechanism of wind-evaporation-sea surface temperature feedback (SST). The anomalous winds (at 850 hPa) induced by the SST anomaly gradient produce low-level convergence and activate upward motion over the SPCZ region, ultimately leading to deep convection and enhanced precipitation there. As a result, the variability in the SPQ leads the changes in the SPCZ by about 5 months. Such extratropical impacts on the SPCZ are independent of the El Niño/Southern Oscillation, which has been demonstrated to have significant impacts on the SPCZ in existing studies. The process study unveils a new connection between the subtropics in the Southern Hemisphere and the tropics, which can potentially enhance predictive understanding of the SPCZ with obvious implications for the weather and climate system.

## 1. Introduction

The South Pacific convergence zone (SPCZ), named by Trenberth (1976), displays a diagonal orientation extending from the western Pacific warm pool to the central tropical Pacific Ocean (120°W and 30°S) in the Southern Hemisphere (SH) (Vincent 1994). The SPCZ is characterized by strong low-level convergence, sea surface temperature (SST) gradients, heavy cloud and precipitation, and weak outgoing long-wave radiation (OLR; Karoly and Vincent 1998). A combination of SPCZ and the intertropical convergence zone (ITCZ) to its northwest produces a spurious 'double ITCZ' (Zhang 2001). Because

of the persistent and strong convective activity, the SPCZ plays an important role in the atmospheric circulation and climate change over both tropical and extratropical Pacific Ocean. For instance, the SPCZ is an essential part of the Walker circulation and the Southern Oscillation (e.g. Trenberth 1976, Streten and Zillman 1984); it influences the cross-equatorial flow (e.g. Vincent 1994, Matthews 2012) and favors the genesis of tropical cyclones (e.g. Huang and Vincent 1983, Vincent *et al* 2011). Rossby waves transmitted from the SPCZ region have impacts on precipitation over the central Andes (e.g. Garreaud and Aceituno 2001, Vuille and Keimig 2004) and surface temperature trends over the Southern Ocean



**Figure 1.** (a) Spatial pattern of the EOF2 mode of the South Pacific ( $140^{\circ}\text{E}$ – $70^{\circ}\text{W}$ ,  $15^{\circ}$ – $60^{\circ}\text{S}$ ) monthly SSTA field for the period 1979–2010 (after removing the monthly mean global average SSTA). EOF2 accounts for 12.2% of the total variance. (b) Correlation map of the JFM-averaged SPQ index with the concurrent SSTA. Positive (red) and negative (blue) value, with correlation significant at the 90% level, are shaded. The JFM-averaged SPQ index (dotted line) defined by the four green boxes (positive regression boxes: B: ( $58^{\circ}\text{S}$ – $36^{\circ}\text{S}$ ,  $173^{\circ}\text{W}$ – $145^{\circ}\text{W}$ ) and D: ( $37^{\circ}\text{S}$ – $17^{\circ}\text{S}$ ,  $103^{\circ}\text{W}$ – $76^{\circ}\text{W}$ ); negative regression boxes: A: ( $47^{\circ}\text{S}$ – $25^{\circ}\text{S}$ ,  $142^{\circ}\text{E}$ – $179^{\circ}\text{W}$ ) and C: ( $59^{\circ}\text{S}$ – $40^{\circ}\text{S}$ ,  $113^{\circ}\text{W}$ – $81^{\circ}\text{W}$ )). (c) The PC2 time series (bold lines) during austral summer associated with EOF2. The correlation between PC2 and SPQ index is 0.74 for the period 1979–2010. (d) Seasonal variations of the standard deviation of the PC2.

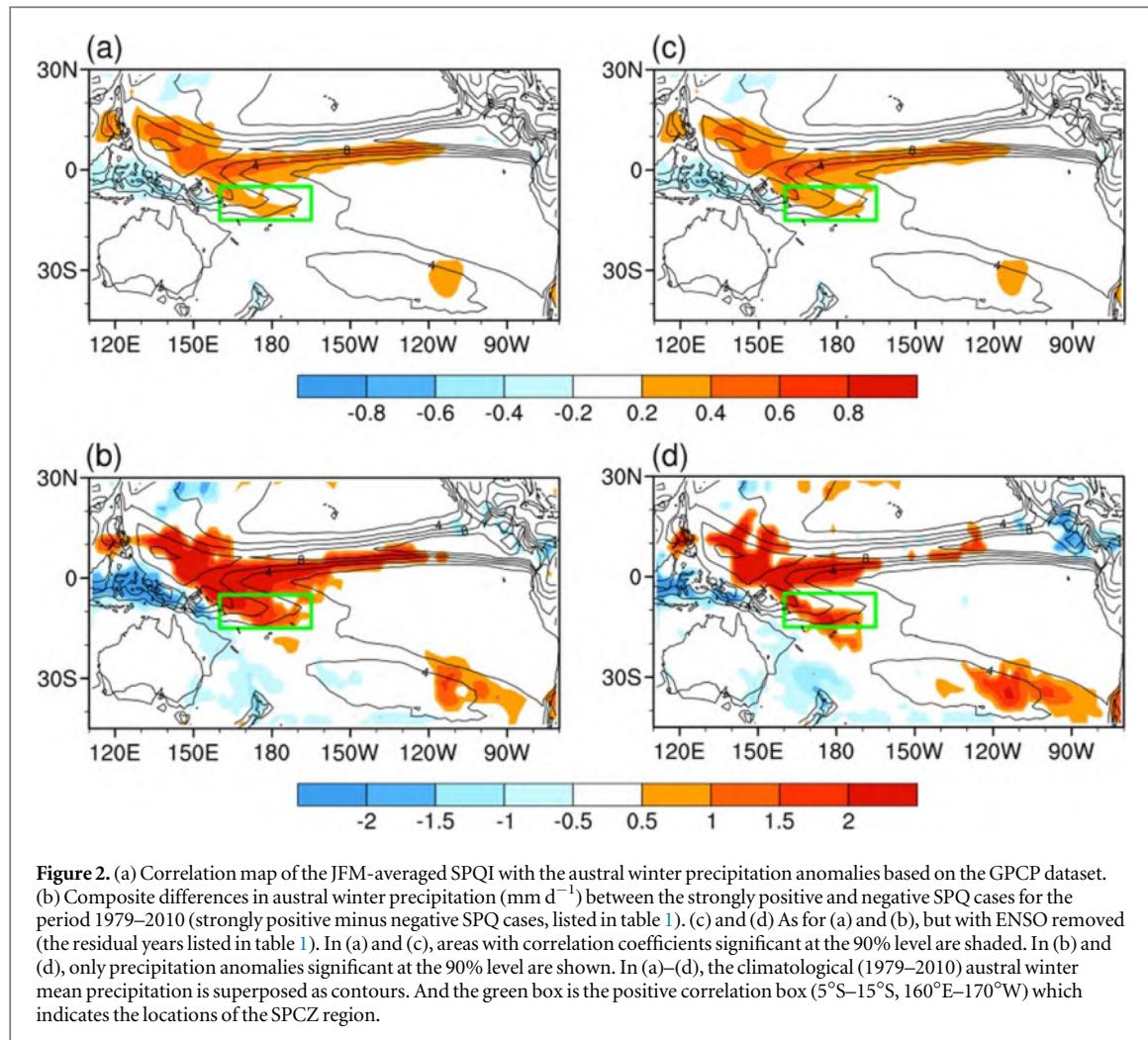
(e.g. Clem and Renwick 2015). Therefore, a better understanding of the SPCZ can benefit both weather and climate studies.

The position of the SPCZ is significantly modulated by the El Niño–Southern Oscillation (ENSO) on interannual timescales (Folland *et al* 2002). During an El Niño event, the equatorial zonal SST gradients decrease when warm water comes from the western Pacific warm pool to the eastern tropical Pacific, resulting in the eastward and equatorward shift of the SPCZ. In contrast, the SPCZ moves westward and poleward during a La Niña event which is attributable to the increased zonal SST gradients (Vincent 1994). On decadal timescales, the SPCZ is modulated by the interdecadal Pacific Oscillation (IPO). For example, Salinger *et al* (2001) found that the annual mean precipitation in the northeast section of the SPCZ manifests a significant difference between a positive (1978–98) and a negative (1946–77) phase of the IPO, due to the modifications in temperature and sea level pressure (SLP). Besides the impacts from the tropics, the SPCZ is also subject to the extratropical influences from the SH. Recently, Ding *et al* (2015) indicated that a quadrupole SST anomaly (SSTA) pattern in the extratropical South Pacific, which was labeled as the South Pacific quadrupole (SPQ) and preceded ENSO by 1 year, ultimately had an influence on the onset

of ENSO through a seasonal footprint mechanism (Vimont *et al* 2003a, 2003b). The seasonal footprint mechanism suggests that an austral summertime SPQ footprint can persist until the following summer and force the atmosphere in the tropics, subsequently leading to anomalous westerlies along the equator which contributes to the onset of an ENSO event. Here, we show that the SPQ in austral summer (January–March (JFM)) has significant impacts on the SPCZ in austral winter (June–August (JJA)) with a lead time of about 5 months, which, to the best of our knowledge, is a new avenue for the extratropical influence on the SPCZ. In addition, since the SPCZ is such a crucial element, which is coupled with various weather and climate phenomena, such extratropical–tropical interaction via the connection between the SPQ and SPCZ can have broad impacts on both the tropics and the subtropics. The remainder of this paper is organized as follows. The data are described in section 2. In section 3, the relationship and mechanism between the SPQ and SPCZ are investigated. Finally, section 4 presents the conclusions and discussion.

## 2. Data

The SSTs from the Hadley Centre Sea Ice dataset (HadISST) are used, which have a horizontal



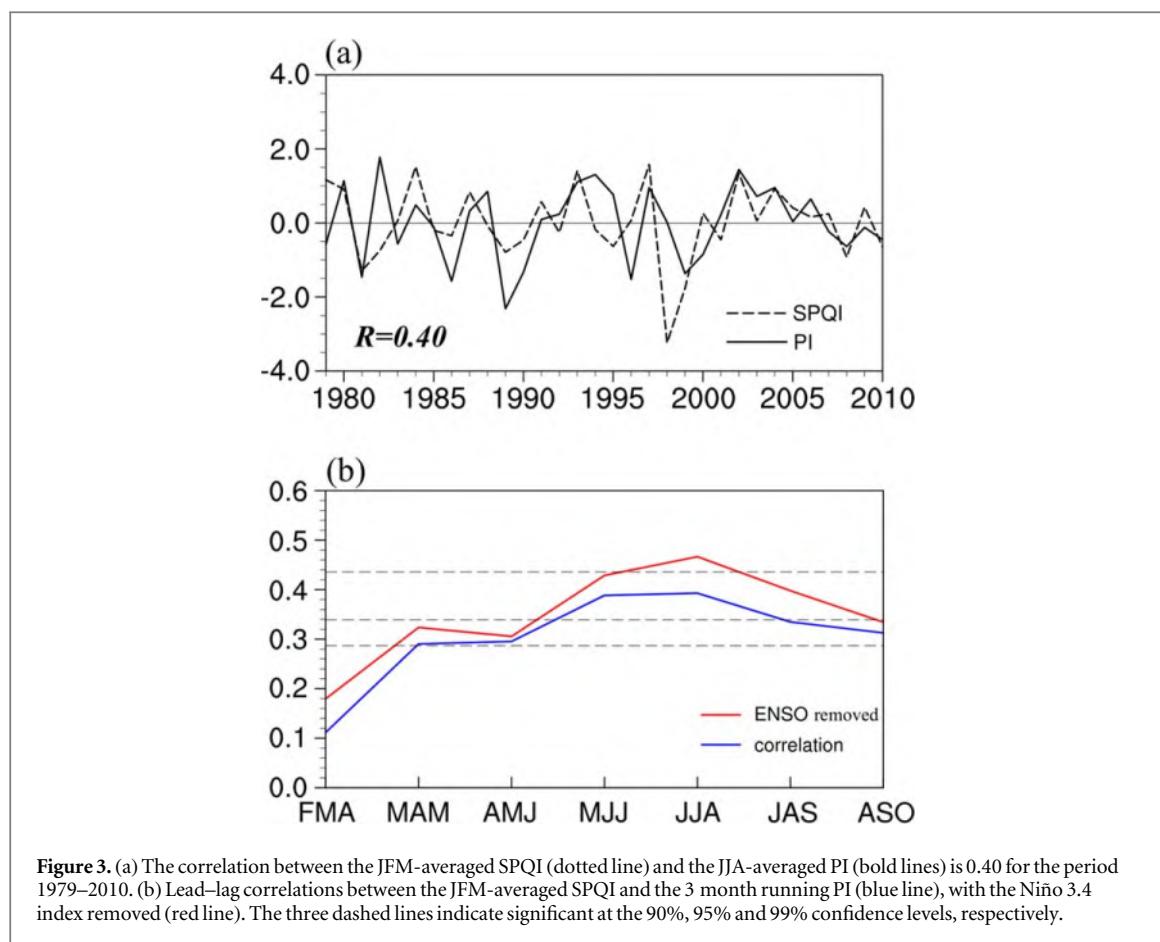
**Table 1.** Classification of the strong positive/negative SPQ events and with the previous austral summer's ENSO (preceding the SPQ by 1 month) removed during the period 1979–2010.

	Strong positive SPQ	Strong negative SPQ
Years	1979, 1980, 1984, 1987, 1993, 1997, 2002, 2004	1981, 1989, 1992, 1998, 1999, 2008, 2010
With ENSO removed	1979, 1980, 1984, 1993, 1997, 2002, 2004	1981, 1992, 1999, 2010

resolution of  $1^{\circ}$  latitude  $\times$   $1^{\circ}$  longitude (Rayner *et al* 2006). The atmospheric variables, such as SLP and winds, are obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; Kalnay *et al* 1996), which has a horizontal resolution of  $2.5^{\circ} \times 2.5^{\circ}$ . To verify the robustness of the results, the SSTs are also obtained from version 3b of the National Oceanic and Atmospheric Administration's (NOAA's) Extended Reconstructed SST dataset (ERSST.v3b), and the atmospheric variables are also obtained from monthly ERA-Interim produced by the European Centre for Medium-Range Weather Forecasts (Uppala *et al* 2005). Only results from HadISST and NCEP–NCAR reanalysis are shown. The monthly precipitation data are from the Global Precipitation Climatology Project

dataset (Huffman *et al* 1997, Adler *et al* 2003) and the Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997); both of these data products have a horizontal resolution of  $2.5^{\circ} \times 2.5^{\circ}$ . The monthly OLR data are from the NOAA (Liebmann and Smith 1996) over the tropical ocean, which are usually used to characterize large-scale tropical convection.

In this study, ENSO is represented with the Niño 3.4 index, which is derived from the SSTA estimates in the Niño 3.4 region ( $5^{\circ}\text{N}$ – $5^{\circ}\text{S}$ ,  $170^{\circ}$ – $120^{\circ}\text{W}$ ). The Niño 3.4 index is extracted from the Climate Prediction Center of NOAA (<https://esrl.noaa.gov/psd/>). JFM is defined as the austral summer, and the austral winter covers JJA. Relative to a given year (0), the preceding year is referred to as (−1).



**Figure 3.** (a) The correlation between the JFM-averaged SPQI (dotted line) and the JJA-averaged PI (bold lines) is 0.40 for the period 1979–2010. (b) Lead-lag correlations between the JFM-averaged SPQI and the 3 month running PI (blue line), with the Niño 3.4 index removed (red line). The three dashed lines indicate significant at the 90%, 95% and 99% confidence levels, respectively.

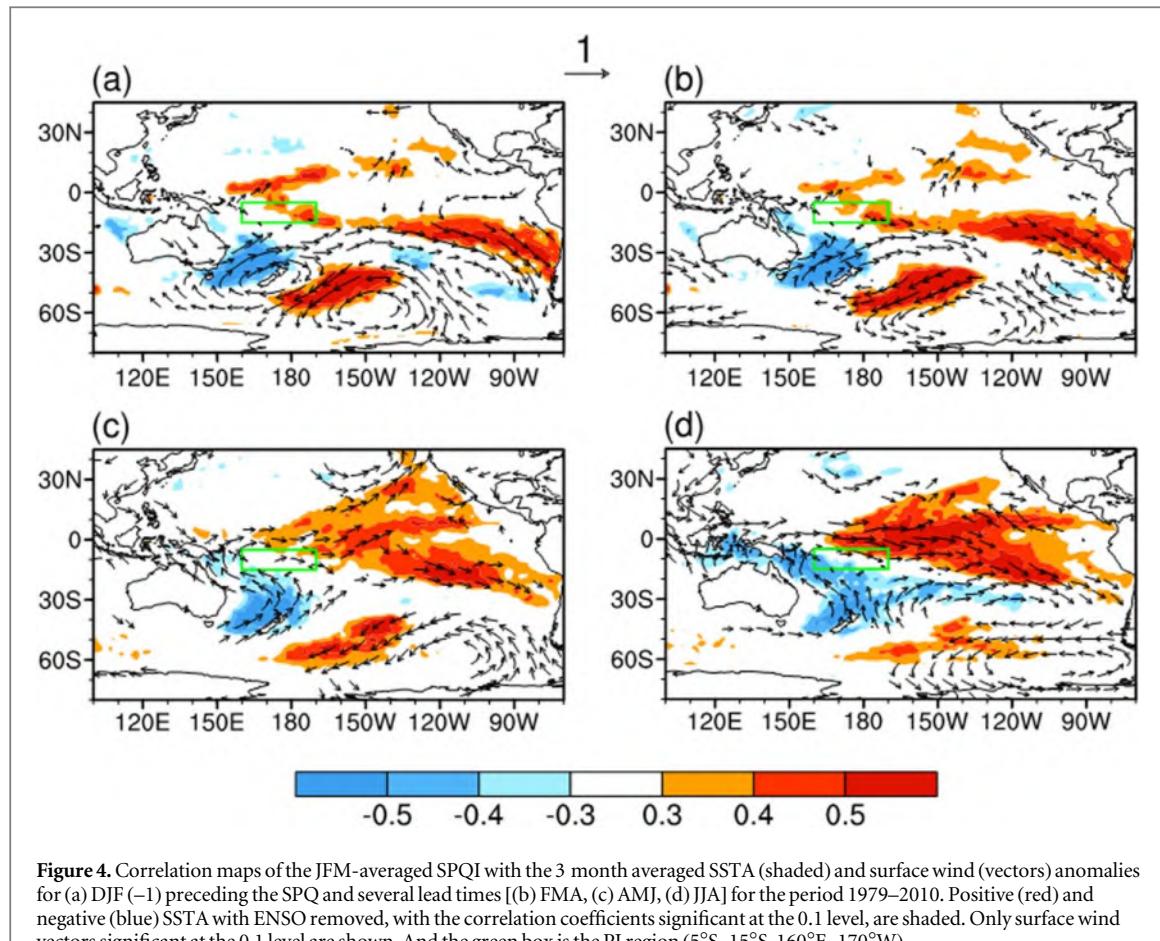
All data from the period of 1979–2010 are used. It is well-known that there was a climate shift around 1976–1977. In addition, the IPO phase remains positive from 1979 to 2011 (Ding *et al* 2016) and it changes to negative at the beginning of 2010s. Therefore, the period from 1979 to 2010 is chosen to avoid the entanglement due to the climate shifts.

### 3. Relationship between the SPQ and precipitation over SPCZ

Following Ding *et al* (2015), the SPQ is defined as the second empirical orthogonal function (EOF2) mode of SSTA in the extratropical South Pacific. Figure 1(a) shows the SPQ obtained using the normalized monthly SSTA in the extratropical South Pacific (poleward of 15°S) from 1979 to 2010 (after removing the monthly mean global average SSTAs). The SPQ accounts for 12.2% of the total SST variance and represents a zonal SSTA pattern with four centers between 30°S and 50°S. The SPQ index (SPQI) is correspondingly defined as the difference between the sum of normalized SSTA over two positive centers (Boxes B and D in figure 1(b)) and the sum of normalized SSTA over two negative centers (Boxes A and C in figure 1(b), Ding *et al* 2015). Figure 1(b) shows the simultaneous correlation between SSTA and the SPQI during austral summer. The correlation

coefficient between the SPQI and principal component of EOF2 (PC2) is 0.74 (statistically significant at the 99.9% confidence level) during austral summer for the period 1979–2010, which demonstrates the accuracy of the SPQI in representing the quadrupole SST mode in the subtropics (figure 1(c)). Figure 1(d) shows the seasonal variation in the standard deviations of PC2 and indicates that the SPQ reaches a large variance in JFM. It is evident that the main SPQ-related significant SSTA are not just located poleward of 20°S but extend into the tropics when the SPQ attains the peak (figure 1(b)).

The relationship between the SPQ and SPCZ is shown in figure 2. The correlation coefficients between the SPQI averaged in austral summer (JFM) and precipitation averaged in austral winter (JJA) are shown in figure 2(a). The climatological mean precipitation during austral winter is superimposed. High correlations exist over both the ITCZ (mainly in the Northern Hemisphere) and SPCZ as highlighted with the green box. Similar patterns can be obtained from the composite made with the differences between the strong positive and negative SPQ cases (figure 2(b)). The positive (negative) SPQ cases are defined as the SPQI larger than one standard deviation (smaller than minus one standard deviation; listed in table 1). However, the analysis in figures 2(a) and (b) includes typical El Niño/La Niña years, which are defined by the Niño 3.4 index when it is larger than one standard



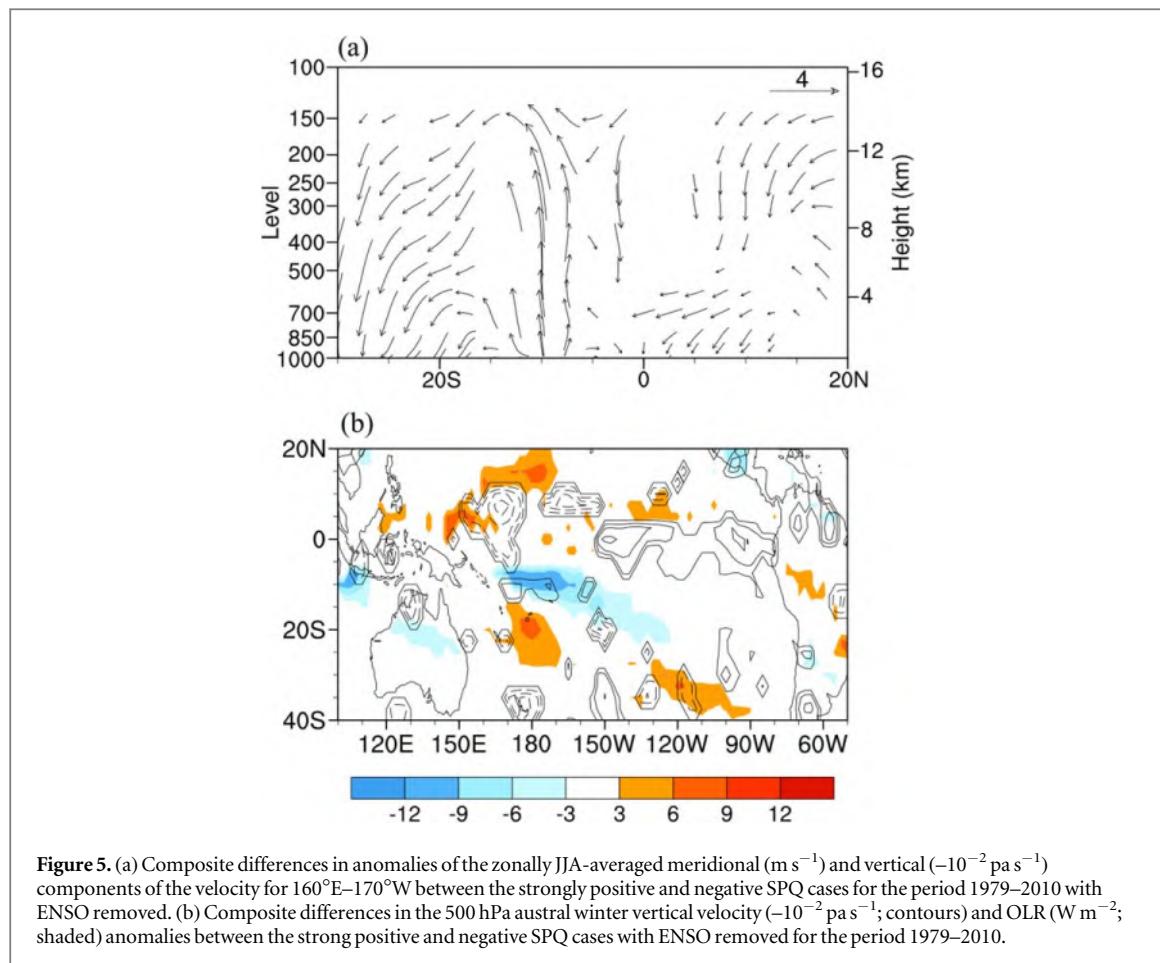
**Figure 4.** Correlation maps of the JFM-averaged SPQI with the 3 month averaged SSTA (shaded) and surface wind (vectors) anomalies for (a) DJF (-1) preceding the SPQ and several lead times [(b) FMA, (c) AMJ, (d) JJA] for the period 1979–2010. Positive (red) and negative (blue) SSTA with ENSO removed, with the correlation coefficients significant at the 0.1 level, are shaded. Only surface wind vectors significant at the 0.1 level are shown. And the green box is the PI region ( $5^{\circ}\text{S}$ – $15^{\circ}\text{S}$ ,  $160^{\circ}\text{E}$ – $170^{\circ}\text{W}$ ).

deviation/less than minus one standard deviation. Previous studies have revealed that ENSO plays a significant role in the SPCZ (e.g. Vincent 1994, Folland *et al* 2002). Meanwhile, ENSO typically reaches maximum amplitude during DJF. As a result, the influence of the JFM SPQ on the JJA SPCZ precipitation needs to be further verified by removing the ENSO effects during DJF. Similar analyses are carried out after filtering out the typical ENSO years, as shown in figures 2(c) and (d) (the residual years are listed in table 1). One can see that the significant correlations, as well as the pronounced differences between positive and negative SPQ cases, remain almost unchanged after removing the ENSO impacts. Therefore, the influence of SPQ on the SPCZ is independent of ENSO, and such relation reveals a connection between the subtropics and tropics in the SH. Similar patterns can be obtained using CMAP dataset (not shown), which indicates the above results are robust.

In particular, there is a close relation between the SPQI and normalized precipitation anomaly averaged over the SPCZ ( $5^{\circ}\text{S}$ – $15^{\circ}\text{S}$ ,  $160^{\circ}\text{E}$ – $170^{\circ}\text{W}$ ) which is referred to as PI hereafter. The mean SPQI in JFM has a significant positive correlation with the mean PI in JJA (figure 3(a)). The correlation coefficient is 0.4 and it is significant at the 95% confidence level. The lead-lag correlations between the SPQ and PI are shown in figure 3(b). The maximum correlation occurs when

the SPQI leads the PI by 5 months, which is consistent with figure 3(a). Such correlation is even higher if ENSO impact is removed (the blue curve in figure 3(b)). Overall, the statistical analyses ensure that impacts of the SPQ on the SPCZ are significant and robust, and the extratropical forcing leads the tropical response by about 5 months.

The spatial patterns of the 3 month running mean SSTA and wind anomalies (at 850 hPa) with respect to the JFM-averaged SPQI are shown in figure 4. It is obvious in figure 4(a) that, during DJF (-1), about 1 month before the SPQ peaks, there are three gyres (between  $30^{\circ}\text{S}$  and  $60^{\circ}\text{S}$ ) in the surface winds coincident with a quadrupole-like SSTA pattern over the South Pacific. Along with the quadrupole structure in SSTA associated with SPQ, the extra-tropics can have impacts on the SPCZ via the mechanism of wind-evaporation-(SST, WES) feedback (Xie and Philander 1994). Suppose that somehow the SSTA in the north is higher than the south. Such north–south SSTA gradient leads to north–south SLP gradient which drives wind anomalies to the north of cold SSTA. When the wind anomalies increase (decrease) to the north of colder SSTA, the evaporation over the northern part of the cold SSTA region tends to increase (decrease) and the SSTA tends to decrease (increase), leading to an enhanced north–south SSTA gradient. Due to the positive WES mechanism, the cold (warm) SSTA



**Figure 5.** (a) Composite differences in anomalies of the zonally JJA-averaged meridional ( $\text{m s}^{-1}$ ) and vertical ( $10^{-2} \text{ pa s}^{-1}$ ) components of the velocity for  $160^\circ\text{E}$ – $170^\circ\text{W}$  between the strongly positive and negative SPQ cases for the period 1979–2010 with ENSO removed. (b) Composite differences in the 500 hPa austral winter vertical velocity ( $10^{-2} \text{ pa s}^{-1}$ ; contours) and OLR ( $\text{W m}^{-2}$ ; shaded) anomalies between the strong positive and negative SPQ cases with ENSO removed for the period 1979–2010.

generates and develops to increase (decrease) wind anomalies. From the central to the eastern Pacific Ocean ( $90^\circ\text{W}$ – $170^\circ\text{W}$  and north to  $30^\circ\text{S}$ ), the reduction of westerlies toward the equator leads to decreased evaporation to the north of positive SSTA. Consistent with the WES feedback, one can see that during DJF and FMA (figures 4(a), (b)), there are no significant SSTAs from the central to the eastern Pacific along the equator and the positive SSTAs can reach  $30^\circ\text{S}$ . In contrast, in AMJ and JJA (figures 4(c), (d)), pronounced positive SSTAs occur along the equator. Over the western Pacific (off the eastern coast of Australia and around  $30^\circ\text{S}$ ), strong southeasterly wind anomalies gradually develop from DJF (figure 4(a)) and prevail in AMJ (figure 4(c)). Consequently, enhanced wind anomalies reinforce the evaporation and the SSTA gradient, which induce an equatorward shift of the negative SSTAs from  $\sim 30^\circ\text{S}$ . Overall, the SPQ-like SSTA footprint persists until austral winter and develops toward the equator. Significant positive SSTA develops to the northeast of the PI region (green box in figure 4) while significant negative SSTA begins to establish in the southwest during the austral winter, which leads to the SSTA gradient along the equator (figure 4(d)).

Furthermore, the anomalous surface winds generated by the SSTA gradient produce low-level convergence

over the SPCZ region, which favors an active upward motion there (figure 5(a)). This intensive upward motion is superposed on the ascending branch of the local Hadley cell and thereby strengthens the convection (figure 5(b)) and precipitation over the SPCZ region. The enhanced convection and precipitation tend to increase the release of latent heat into the atmosphere, which in turn favors the enhancement of the low-level convergence, upward motion, and convective precipitation. Ultimately, these positive feedback processes cause significant positive precipitation anomalies over the SPCZ region, and establish a good correlation between the SPQ and precipitation over the SPCZ as shown in figure 3.

#### 4. Conclusion and discussion

The relationship between the SPQ in austral summer and the SPCZ in austral winter is examined. It is found that, besides the well-known influences of ENSO and IPO, the SPQ in the extra-tropics in SH can also have substantially impacts on the SPCZ, which tends to strengthen the SPCZ precipitation. Strong positive (negative) SPQ cases are followed by positive (negative) precipitation anomalies over the SPCZ region. The processes described in section 3 are evidence that the SPQ-induced SSTA persists until austral winter and develops toward the equator via WES feedbacks, leading to the SSTA gradient and a

large-scale surface convergence, ultimately causing deep convection and precipitation over the SPCZ region.

Ding *et al* (2015) and Qin *et al* (2017) suggest that the SPQ is forced by a wave train with three centers of SLP anomalies and potentially triggers the onset of ENSO. During this process, the negative SSTA in the west and positive SSTA in the east develop and shift to the tropical Pacific, subsequently enhancing the SSTA gradient and generating low-level convergence over the tropical Pacific. Therefore, further analysis of the evolution of the SPQ within climate simulation models is necessary. From figure 2, notable positive precipitation anomalies are also exhibited in the western part of the ITCZ. Thus, additional research is required to discover the impact of the SPQ on the precipitation in the Northern Hemisphere tropical Pacific.

Furthermore, previous studies showed that the SPCZ plays an important role both in the tropics and extra-tropics. In this regard, an issue is naturally raised about whether the SPQ is related to the cross-equatorial flow and tropical cyclones through the SPCZ. Liu *et al* (2017) examined the influence of SH atmospheric variability on the South China Sea summer monsoon via changing cross-equatorial easterly flows. Pu *et al* (2018) demonstrated that the boreal spring Victoria mode (extratropical EOF2 SSTA pattern in North Pacific; Vimont *et al* 2003a, 2003b) has an impact on the boreal summer tropical cyclone over the northwestern Pacific. These studies suggest that the extratropical atmospheric and SST variability in either the South or the North Pacific does provide useful information for the tropics. Further research is required to perform analysis on cross-equatorial flow and tropical cyclones with the influence of the SPQ.

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