The South Pacific Convergence Zone (SPCZ): A Review

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ABSTRACT

The circulation features associated with the South Pacific convergence zone (SPCZ) and its accompanying cloud band are reviewed and discussed. The paper focuses on the following topics: location, structure, and characteristics of the SPCZ; theories and observations concerning its existence; the significance and scope of the SPCZ in global-scale circulation patterns; quasi-periodic changes in its location and strength; and synoptic-scale features within its regional influence (e.g., cyclones, subtropical jets). It concludes with some challenging problems for the future.

1. Introductory remarks

The South Pacific convergence zone (SPCZ) contains one of the earth’s most expansive and persistent convective cloud bands, and is recognized as playing a significant role in global-scale circulation patterns. Although first depicted in the surface analyses of Bergeron (1930), the vast extent of the SPCZ, both spatially and temporally, was not fully appreciated until satellite imagery became available in the early 1960s (e.g., Hubert 1961). Since that time, numerous studies have been conducted of this rather intriguing phenomenon. The primary purpose of this paper is to provide a convenient summary of the knowledge gained from those SPCZ studies. In that context, the paper focuses on a review of past and exiting theories and observations about the SPCZ. It is important to note that it is not the intent of the paper to choose between, or criticize, contrasting opinions where they may occur. It should also be mentioned that, with regard to the observational results presented herein, it was frequently necessary to rely on those obtained during the first special observing period (SOP-1) of the First GARP (Global Atmospheric Research Program) Global Experiment (FGGE); results, particularly above the surface, are otherwise quite sparse in the literature. For this reason, some of the findings cited in this paper, especially those toward the end, are for January and February 1979. In these cases, it was difficult to draw any general conclusions.

The organization of the paper is as follows. In section 2, the location, structure, and characteristics of the SPCZ are described, with attention devoted to seasonal changes. This is followed by a summary of theories and observations concerning its origin and maintenance (section 3). Next, the significance of the SPCZ and its role within global-scale circulation patterns are discussed (section 4). Section 5 presents a synopsis of the quasi-periodic behavior of the SPCZ. The focus is on intraseasonal and interannual oscillations, since seasonal changes are discussed in section 2. Section 6 discusses some of the synoptic-scale features associated with the SPCZ, such as cyclones, subtropical jet streaks, and storm tracks. Here, the results discussed are only for a 2-week period in January 1979. Finally, in section 7 concluding remarks are given and some challenging problems are offered. It will be seen that some of the problems arise because of the lack of observational evidence, especially outside the SOP-1 of FGGE. Before proceeding, the author would like to state that he is indebted to many of his fellow scientists whose solicited contributions and comments made this paper possible. These colleagues are recognized in the acknowledgments section.

2. Location, structure, and characteristics

The name, SPCZ, is generally attributed to Trenberth (1976). In its mean annual position the axis of the SPCZ stretches from New Guinea east-southeastward to about 30°S, 120°W. In its northwestern sector the SPCZ becomes more zonally oriented and merges with the intertropical convergence zone (ITCZ), which extends westward into the Indian Ocean. Figure 1, extracted from Trenberth (1991a), serves as a representative example of the main surface features and the cloud band associated with the average location of the SPCZ. It shows, as Trenberth (1976, 1991a) and others (e.g., Streten and Zillman 1984; Kiladis et al. 1989; Kodama 1992, 1993) have noted, that the SPCZ lies in a region...
of low-level moisture convergence, between the predominantly northeasterly flow west of the eastern Pacific subtropical high and the cooler predominately southeasterly flow from higher latitudes. It is worth noting that Fig. 1 is a schematic representation of the mean circulation features that undergo changes on several temporal scales. For the present, only seasonal changes are discussed; longer- and shorter-term changes will be addressed in sections 5 and 6, respectively.

Figure 2 shows the mean sea level pressure (MSLP) patterns for the months of January and July, obtained as 6-yr averages (1985–90) from the World Climate Research Programme/Tropical Oceans and Global Atmosphere (WCRP/TOGA) archive II European Centre for Medium-Range Weather Forecasts (ECMWF) analyses. In January, the most prominent feature is the trough of low pressure that extends eastward from the monsoonal low centered over northern Australia across the Pacific to a location near the equator and 130°W. The western part of this trough is commensurate with the zonal portion of the SPCZ. Also shown is the trough associated with the diagonal portion of the SPCZ, which extends southeastward from 10°S, 170°E to 30°S, 160°W. In July, the pattern has changed drastically. The trough of low pressure is now located along a line that stretches from the low centered over Southeast Asia, associated with their summer monsoon, east-southeastward across the Pacific to just east of the date line where it then remains close to the equator. In contrast to January, there is a high pressure center located over southern Australia and no obvious pressure trough over the South Pacific. Comparing the MSLP patterns in Fig. 2 to the one in Fig. 1 reveals that Trenberth’s (1991a) schematic is approximately a blend of the January and July distributions.

The other pattern shown in Fig. 1 is surface streamlines. For comparison, Fig. 3 shows the 6-yr monthly distributions of streamlines and isolachs at the surface (10 m) for January and July. In January, northeast trade winds extend across the entire tropical and subtropical North Pacific. In the South Pacific and over northern Australia, there is strong confluence into the monsoonal trough and SPCZ region. In July, southeast trades prevail over the South Pacific and there is an anticyclone over southern Australia. There is little evidence of the existence of the SPCZ (i.e., no obvious confluent zone). As was seen in the pressure pattern, the streamline field in Fig. 1 appears to be an approximate blend between the flow fields depicted for January and July in Fig. 3. It is worth noting that the pressure and wind fields shown in Figs. 2 and 3 are in good agreement with those given by Sadler et al. (1987). The latter is an excellent reference of the long-term mean monthly distributions of MSLP, surface wind and wind stress, and sea surface temperature in the Tropics and subtropics.

As stated in the introduction, the SPCZ contains one of the earth’s most expansive and persistent cloud bands. Early evidence of this was given by Streten (1973) who used 5-day averages of satellite mosaics over a 3-yr period (1968–71) in the Southern Hemisphere to construct seasonal means of percent cloud cover. He found that the SPCZ contained the highest frequency of clouds in all seasons, with maximum annual values in excess of 40% stretching from New Guinea to approximately 30°S, 120°W. A similar axis of maximum cloudiness was found by Atkinson and Sadler (1970) and Gruber (1972). In later studies, however, it was determined that the SPCZ cloud band is most intense in southern summer. For example, in a study by Meehl (1987), the monthly mean values of outgoing longwave radiation (OLR) showed a more ex-
tensive and convectively active cloud band in January than in the other three midseason months (Fig. 4).

There is additional evidence that indicates the SPCZ is generally more active in southern summer than at other times during the year. As an example, consider Fig. 5, which shows maps of vertical $p$ velocity ($\omega$) at 500 hPa for the four 3-month seasons, June–August, September–November, December–February, and March–May. As for Figs. 2 and 3, these results were obtained from the 6-yr averages (1985–90) of WCRP/TOGA archive II ECMWF analyses. The figure clearly shows that midtropospheric upward motion along the SPCZ, particularly in the diagonal portion, is much stronger and extensive in December–February than in other seasons.

A convenient summary of the seasonal changes that occur in the SPCZ region is provided by Meehl (1987). He illustrates the annual cycle of several variables based on island station reports across the Indian and Pacific Oceans. His results clearly illustrate the southward and eastward progression of different measures of convective activity from India in July to the SPCZ region in January. For example, his time series of monthly means show minimum surface pressure anomalies, maximum cloudiness, minimum OLR, and maximum precipitation reaching the zonal portion of the SPCZ, near northern Australia, by January. From January to March these variables propagate across the western Pacific Ocean to about the date line. In the diagonal portion of the SPCZ the respective minima and maxima are not as distinct but show quasi-steady values from December to March. An example of Meehl’s results is shown in Fig. 6, which depicts sea level pressure anomalies and precipitation at stations from India to the eastern Pacific. It is seen that the lowest surface pressures and highest precipitation rates in the SPCZ region take place in the southern summer season. Because all of the variables discussed thus far have shown the SPCZ to be more intense in southern summer, the emphasis for much of the remaining paper will be on that season. Furthermore, as stated in section 1, many of the detailed analyses of SPCZ features were available only for the SOP-1, FGGE period (i.e., southern summer months of January and February).

With this in mind, we shall continue our discussion of the location, structure, and characteristics of the SPCZ. Figure 7 shows maps of precipitation, sea surface temperature (SST), and surface wind convergence for January, extracted from Kiladis et al. (1989). They note that, “the surface convergence maximum associated with the SPCZ lies to the south of the axis of maximum precipitation, typical of tropical convergence zones” [e.g., GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE) A/B-scale ship array]. They further note, as Fig. 7 shows that, “maximum precipitation lies to the south of the axis of maximum SST.”

The mean flow patterns at 200 and 850 hPa for January are shown in Fig. 8. These charts were obtained from the same ECMWF dataset used to derive earlier figures. Of primary interest here are the two Southern Hemisphere upper-level anticyclones that are approximately superimposed on (slightly east of) two low-level cyclones. This pair of circulation systems, together with the ridge (at 200 hPa) and trough (at 850 hPa) between them, lies along the axis of upper-level out-
Fig. 4. Eight-year means of OLR (W m$^{-2}$) for the period June 1974–November 1983 (1978 missing) for (a) July; (b) October; (c) January; and (d) April. Areas of OLR $\approx 220$ W m$^{-2}$ are shaded (extracted from Meehl 1987).

Flow and lower-level inflow associated with the zonal portion of the SPCZ. There is also an upper-level ridge (lower-level trough) that extends southeastward from the easternmost anticyclonic (cyclonic) center. This feature is aligned along the approximate location of the diagonal portion of the SPCZ. The flow pattern at 200 hPa is in good agreement with that presented in the atlas by Sadler (1975).

The upper-tropospheric flow regime and its relationship to the SPCZ cloud band are now examined in more
Figure 9 shows depictions of the mean state upper-level flow given by three different sets of authors [Sadler (1972) for January at 200 hPa, Madden and Zipser (1970) for March–April 1967 at 250 hPa based on the Line Islands Experiment, and Vincent (1982) for 10–18 January 1979 at 200 hPa based on FGGE SOP-1 data]. The latter two references also show the location of the cloud band. Similar patterns are evident in each depiction and are also comparable to those in Fig. 8. An anticyclone is present near 10°S, just west of the date line, with a ridge extending east-southeastward from it to the central and, sometimes, eastern Pacific. The ridge is collocated with the cloud band, a position that is favorable for providing divergent outflow to sustain the convection. It could also be argued that the deep convection within the SPCZ causes the ridge. A col area is located just north of the equator near the date line, with a prominent trough line extending from it along an axis that parallels the ridge line. In the depiction by Vincent (1982), there is another trough line to the southwest of the ridge line and cloud band. It is interesting to note that Manabe et al. (1970) were able to reproduce the trough–ridge pattern illustrated in Fig. 9 with an early version of the Geophysical Fluid Dynamics Laboratory (GFDL) general circulation model (GCM), which contained a convective adjustment scheme. Without the scheme (i.e., with their “dry” model), the flow across the subtropical South Pacific was essentially zonal. Their results suggest, therefore, that SPCZ convection causes the upper-tropospheric ridge.

The relationship between the surface pressure trough, alluded to earlier, and the SPCZ cloud band are shown in Fig. 10 for a 9-day period during SOP-1, FGGE, 10–18 January 1979. The figure was created from the results of Huang and Vincent (1983). Note that the pressure trough lies along the southwestern edge of the cloud band and, thus, is poleward and westward of the upper-level ridge line discussed above. It has been observed or suggested by several authors that the trough–ridge system in the vicinity of the SPCZ tilts poleward and westward with height (e.g., Trenberth 1976, 1991a; Vincent 1982; Kiladis et al. 1989; Kiladis and Weickmann 1992a). This tilt supports the suggestion of many investigators, namely, that the diagonal portion of the SPCZ is highly baroclinic.

The vertical structure of the zonal and diagonal portions of the SPCZ were depicted by Vincent (1982) for the same period used to construct Fig. 10. Selected as an example is Fig. 11, which shows vertical cross sections of the 9-day averages (10–18 January 1979) of several variables along a line that is perpendicular to, and crosses, the diagonal portion of the SPCZ cloud band. The center of the cloud band for this period was 25°S, 142.5°W, and the cloud band width (convectively active portion) was the equivalent distance of about 10° of latitude—that is, 5° each side of the center point. The figure shows that a deep layer of moist air occurs...
Fig. 6. Annual cycle of long-term mean station data of (a) sea level pressure and (b) precipitation, plotted as deviations of 3-month running means from the annual mean. Stippling denotes highest pressures in (a) and greatest precipitation in (b), and vice versa for cross-hatching. Each tic mark on the horizontal axes indicates 5.0 mb in (a) and 100 mm month$^{-1}$ in (b) (extracted from Meehl 1987).

in conjunction with the narrow band of maxima in low-level convergence, upper-level divergence, and rising motion. Outside the cloud band, drier air is descending. Near the center of the cloud band the relative vorticity is near zero at all levels; however, away from the center, there is cyclonic vorticity to its southwest and anticyclonic vorticity to its northeast throughout the troposphere.

Temperature anomaly and wind cross sections in Fig. 11 offer the most revealing insight into the physical processes that occurred within the cloud band and its environment during the 9-day period. Anomalies were calculated as a grid point's departure from the average of all grid points along each constant pressure level. It is seen that temperature anomalies in the middle and upper troposphere are appreciably higher within the band than they are outside the band, suggesting that latent heat dominates over adiabatic cooling in the strong ascending motion. Wind speeds show minimum vertical shear near the center of the cloud band and strong vertical shear toward the edges of the band, particularly to its southwest.

This section closes with a comparison of the vertical profiles of convective heating between the SPCZ and other tropical regions. Figure 12 shows such profiles derived from the $Q_1$-budget technique of Yanai et al. (1973). The profile on the left is taken from Miller and Vincent (1987) and represents the average convective heating for the SPCZ region bounded by $7.5^\circ$S$-27.5^\circ$S and $170^\circ$E$-135^\circ$W, for the period 10-18 January 1979. The profiles on the right are those determined by other investigators using similar methodology (Reed and Recker 1971; Nitta 1972; Yanai et al. 1973; Thompson...
In the first three studies, data gathered over the Marshall Islands were used. Despite differences in the large-scale conditions (i.e., the periods of study were different), and analysis techniques, the three heating profiles are similar. They all show maximum heating in the 500–400-mb layer, comparable to the results of Miller and Vincent. Thompson et al. used data from the GATE B-scale ship array during phase III and obtained a somewhat different heating profile. Their profile shows maximum heating at a much lower level (~600 mb) than those obtained over the Marshall Islands area. Thompson et al. suggest that deep clouds and convection frequently dominate the Marshall Islands area, while multiple cloud layers that are often observed in the GATE region, yield a lower level of maximum heating. Finally, although it was not possible to reconstruct a vertical profile of heating from the study by Song and Frank (1983), they showed for the A/B-scale area during phase 1 of GATE that maximum convective heating, in cases when precipitation rates exceeded 0.5 mm h⁻¹, occurred near 550 mb. However, when rates were less than 0.5 mm h⁻¹, the maximum occurred below 800 mb. It would appear that if their rainfall-rate categories were combined, the net profile that would result would be similar to that of Thompson et al. Thus, it seems that the results for the South Pacific are more in line with those for the western portion of the North Pacific Ocean than with those for the GATE area.

It is important to note that the profiles shown in Fig. 12 represent mean values over areas that contain convective systems, as well as clear regions. Miller and Vincent (1987) examined the average vertical distribution of convective heating for a 12-h period on 12 January 1979 near the center of a cyclone in the SPCZ cloud band. They found that the maximum value was several times greater than the maxima shown in Fig. 12. Also, there was a much deeper layer of high values of convective heating that extended well into the upper troposphere.

3. Origin and maintenance

As discussed and shown above, the summertime SPCZ consists of a zonal portion, generally located over the western Pacific in the "warm pool" region, and a diagonal portion, oriented northwest–southeast. There have been several attempts to explain the location, orientation, and strength of each of these components of the SPCZ, but because the explanations are somewhat interrelated (i.e., not mutually exclusive), it is difficult to separate them into distinct hypotheses. Nevertheless, an attempt is made here to sort out some of the ideas regarding the origin and maintenance of the SPCZ. One theory is that the SPCZ, particularly the zonal portion, owes its existence to warm underlying SSTs or, more explicitly, to SST gradients (e.g., von Storch et al. 1988; Kiladis et al. 1989; Trenberth 1991a; Kiladis and Weickmann 1992a). The scenario in this regard is as follows: SST gradients impose pressure gradients that in turn drive low-level winds that result in moisture convergence. This argument is similar to that proposed by Lindzen and Nigam (1987) for the existence of the ITCZ in the western and central Pacific. In brief, they suggest that SST gradients account for a significant portion of the forcing of low-level
winds (i.e., beneath the trade-wind inversion), resulting in mass convergence. As a consequence, high-$\theta_e$ air accumulates near the rising branch of the ITCZ where the convergence (primarily of water vapor) helps to concentrate the location of deep convection and the accompanying latent heat release that occurs in the middle and upper troposphere. They state that moisture convergence tends to be a maximum where SST gradients are greatest. They further state that while latent heating undoubtedly drives the upper-level outflow, there is no compelling reason to suppose it will impact on the low-level convergence. In numerical simulations by Lindzen and his collaborators, the best results were obtained when the effects of both low-level forcing by SST gradients and upper-level forcing by latent heat release were coupled. However, they could not explicitly determine the role that latent heating plays in producing sufficient low-level convergence. Finally, they note that in the region occupied by the zonal portion of the SPCZ, forcing appears to be due primarily to zonal gradients of SST, although they also found that zonal variations in the meridional gradients could be important. Support for this theory can be seen in the map of surface temperatures for January 1986 (Fig. 13). Note that the warmest SSTs (nearly 304 K) occur in the western Pacific along about 5°–10°S, between 150° and 170°E. Also note that the SSTs along this latitude decrease to about 302 K between 170°E and 170°W. It has been shown in several figures thus far that the zonal portion of the SPCZ frequently lies close to this latitude belt between 150°E and 170°W.

Another theory for the origin and maintenance of the SPCZ is that it is due to land–sea distributions. There have been a few studies, primarily using GCMs (e.g., Kalnay et al. 1986; and Kiladis et al. 1989), that investigated the potential influence of the three main landmasses in the Southern Hemisphere on the location of the SPCZ, particularly during the summer season when continental heating is a maximum and the SPCZ is most intense. The net result of these studies suggests that the positioning of the land–ocean distribution has little influence on the location of the SPCZ; however, in the experiments by Kiladis et al. (1989), changes in the heating and circulation patterns over Australia in January did have an impact on the strength of the

Fig. 9. Upper-tropospheric winds and SPCZ cloud band based on (a) mean January at 200 hPa (wind speeds in knots) adapted from Sadler (1972); (b) a schematic of streamlines at 250 hPa during the Line Islands Experiment, extracted from Madden and Zipser (1970); (c) streamlines and isotachs (m s$^{-1}$), extracted from Vincent (1982). Trough lines are dashed and ridge lines are zig-zag; shaded areas in (b) and (c) represent SPCZ cloud band; for reference, crosses indicate common latitude–longitude locations (10°S, 180° and 20°S, 150°W) on each diagram.

Fig. 10. Average sea level pressure and OLR $\leq$ 225 W m$^{-2}$ (shaded) for 10–18 January 1979. Trough line indicated by dashed line. This figure was compiled from diagrams presented by Huang and Vincent (1983).
SPCZ. They found that the removal of the continent of Australia in their GCM run destroyed the southern monsoon and weakened the zonal portion of the SPCZ.

Still another theory, again primarily related to the zonal portion of the SPCZ, was suggested by Davidson and Hendon (1989). They investigated the interactions
Among the three main components of the Southern Hemisphere monsoon (Indonesian monsoon, Australian monsoon, and SPCZ) during the period December 1978–January 1979 using winds and relative vorticity at 850 hPa. They were able to trace the path of three progressive eastward-moving cyclonic (and anticyclonic) vortices that enhanced SPCZ convection and strengthened the South Pacific vortex, back to northern Australia in one case and to the Indonesian sector in the other two cases. They hypothesized that these patterns of downstream development were consistent with the eastward-propagating energy dispersion process described by advocates of linear barotropic dynamics among the three main components of the Southern Hemisphere monsoon (Indonesian monsoon, Australian monsoon, and SPCZ) during the period December 1978–January 1979 using winds and relative vorticity at 850 hPa. They were able to trace the path of three progressive eastward-moving cyclonic (and anticyclonic) vortices that enhanced SPCZ convection and strengthened the South Pacific vortex, back to northern Australia in one case and to the Indonesian sector in the other two cases. They hypothesized that these patterns of downstream development were consistent with the eastward-propagating energy dispersion process described by advocates of linear barotropic dynamics.

At present, the most appealing hypothesis regarding the origin and maintenance of the diagonal portion of the SPCZ focuses around mechanisms involving tropical–midlatitude interactions and/or midlatitude influences. For example, Kiladis et al. (1989) conclude that the central and eastern parts of the SPCZ reflect the preferred storm tracks that propagate from lower to higher latitudes when the tropical convergence zone interacts with transient troughs in the midlatitude westerrms. Their results are compatible with those of other authors (e.g., Streten and Zillman 1984; Vincent 1985; Hurrell and Vincent 1990). Other investigators have stressed the importance of maintaining the diagonal portion of the SPCZ through disturbances and frontal activity that propagate equatorward from higher latitudes, generally in the vicinity of New Zealand (e.g., Streten 1973; Webster and Curtain 1975; Trenberth 1976, 1991a; Kiladis and Weickmann 1992b). These systems tend to strengthen the low-level convergence between themselves and the quasi-stationary high in the eastern Pacific.

An example of some of the processes described above was illustrated in the GCM results of Hurrell and Vincent (1992). They conducted a number of experiments in which SSTs (and thus SST gradients) were reduced by varying amounts in the Southern Hemisphere tropical western Pacific (i.e., zonal portion of the SPCZ). Within a few days, the upper-tropospheric divergent outflow, induced by the heating, was substantially reduced. In the same time frame the subtropical jet, located just southeast of the divergent outflow and in the vicinity of the diagonal portion of the SPCZ, decreased by a factor of 2. In addition, poleward- and eastward-propagating Rossby waves, present in their control run, were essentially absent. Thus, it appears that the baroclinic structure of the diagonal portion of

![Fig. 13. Surface temperatures over land and ocean (SSTs) in kelvins for January 1986, taken from WCRP/TOGA ECMWF archive II dataset.](image)
the SPCZ was influenced by tropical heating (SST gradients, in particular). Hurrell and Vincent (1991, 1992) showed that both midlatitude wave activity and divergent outflow from a tropical heat source were important in maintaining the subtropical jet. Figure 14 summarizes their results, which were obtained as 15-day means for the period 6–20 January 1979. The top panel in Fig. 14 shows the location of the subtropical westerly jet in question; it is centered at about 25°S, 170°W, and has a maximum strength in excess of 30 m s⁻¹. The remaining panels depict contributions to the acceleration of the zonal wind by the two most important terms in the localized E–P flux equations of Trenberth (1986). These are the Coriolis force due to the diabatically driven divergent meridional wind (fv*) and the E–P flux divergence (V·E), which is a measure of the net mean forcing by eddies on the time mean flow. It is seen that the tropical forcing (fv*) acts to accelerate the jet in its entrance region, whereas the midlatitude forcing (V·E) acts to decelerate it. In the exit region, both terms act to accelerate the jet. The net effect appears to move the jet eastward during the 15-day period, as was observed. Moreover, the results verify (at least for this case study) that both tropical and extratropical forcing are important in maintaining the jet, which is an integral part of the strength and location of the diagonal portion of the SPCZ.

4. Significance in global-scale circulations

In preceding sections, the persistence and expase of the SPCZ was established. In this section the significance of the SPCZ with regard to global-scale circulation patterns is demonstrated. Krishnamurti et al. (1973), based on their analysis of upper-tropospheric winds, together with Atkinson and Sadler's (1970) nephanalysis, noted that there were three principal regions of tropical convection during northern winter. They stated that the convection centers must account for the three waves containing subtropical jet streams in the Northern Hemisphere and the three midoceanic troughs in the Southern Hemisphere. They concluded that the regions of convection provide a major link between the flows in the two hemispheres. Since one of their troughs is an integral part of the SPCZ, and the SPCZ is a dominant convection region in the Southern Hemisphere, it seems reasonable that the SPCZ might play an important part in the cross-equatorial flow over the western and central Pacific. This feature is readily identifiable in Fig. 8, where outflow from the SPCZ region is seen to penetrate into the Northern Hemisphere between the longitudes of approximately 150°E and 160°W in January.

Within the confines of the Southern Hemisphere, there are several measures of the importance of the SPCZ. The interactions that occur between the ITCZ and midlatitude systems that penetrate into the subtropics across the western and central Pacific have already been alluded to as an important mechanism for causing and maintaining the SPCZ. The SPCZ is also known to be an integral part of the Southern Oscillation (SO) and the Walker circulation (e.g., Trenberth 1976; Streten and Zillman 1984; van Loon and Shea 1987). More will be said in section 5 about the role of the SPCZ with regard to the SO and other quasi-periodic circulation patterns.

Attention is now focused on results in which quantitative estimates of the significance of the SPCZ have been given. Hurrell and Vincent (1987) performed a diagnosis of eddy energy budget terms in the SPCZ and

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**Fig. 14.** Averages at 200 hPa of the zonal wind component (m s⁻¹, upper), E–P flux divergence (m s⁻¹ day⁻¹, middle), and fv* (m s⁻¹ day⁻¹, lower), for the period 6–20 January 1979. Sources of zonal wind acceleration greater than or equal to 10 m s⁻¹ day⁻¹ are shaded.
other Southern Hemisphere tropical regions of similar areal extent for a 15-day period during SOP-1, FGGE. They computed vertical integrals that were area averaged from 0° to 30°S, for four subregions bounded by the following longitudes [Africa (AFR), 25°W–65°E; Australia (AUST), 65°–155°E; SPCZ, 155°E–115°W; South America (SA), 115°–25°W]. Their results are summarized in Fig. 15, which shows 1) the energy cycle for all regions being dominated by a generation of eddy potential energy by diabatic heating processes, a conversion of eddy potential to eddy kinetic energy, and a dissipation of eddy kinetic energy; and 2) the energy cycle for the SPCZ being dominant over that for the other three regions. It is also seen that the eddy kinetic energy content is substantially greater in the SPCZ than in other regions. Thus, it is speculated that the SPCZ makes a significant contribution to the eddy energy budget of the Southern Hemisphere Tropics in January.

In an earlier paper, Huang and Vincent (1985) found that the standing eddies were responsible for nearly all of the conversion of potential to kinetic energy (CE) in the SPCZ and that the conversion was a maximum in the 300–250-hPa layer. In that paper and a later one (Huang and Vincent 1988) they found that wavenumber 4 dominated the CE conversion in the Southern Hemisphere Tropics in the 10–24 January 1979 period when the SPCZ was quasi-stationary, very intense, and located east of its normal position. One of the four waves (the dominant one) corresponded to the SPCZ, while the other three were centered over the three continents of Africa, Australia, and South America. From 24 to 27 January the SPCZ convection and its associated wave activity and subtropical jet all decayed. Subsequently, there was a realignment of the long waves to a wavenumber 3 pattern that lasted until the end of their study period (13 February). The convection centers associated with the latter pattern were centered over the western Indian Ocean, the western Pacific, and South America. It is not currently known if this transformation from wavenumber 4 to 3 (and presumably back to 4) is a regular feature of the tropical South Pacific. If it is, the meandering of the SPCZ between the central and western Pacific may play a key role. Further reference to this feature is given in section 5.

Another quantitative measure of the significance of the SPCZ is given in the precipitation estimates of Vincent et al. (1991a). They used the $Q_i$-budget method of Yanai et al. (1973) to compute monthly mean rainfall rates (as the budget residual) for the regions shown in Fig. 16 from June 1984 to May 1987. All regions, with the possible exception of the SPCZ, exhibited a distinct annual cycle with about twice as much rain in midsummer as in midwinter; however, the SPCZ had more rain during the 3-yr period than any of the other regions. In the last two years (i.e., June 1985–May 1987) the SPCZ had an annual average rate of 6.1 mm day$^{-1}$. By normalizing the corresponding values for other regions, based on a value of 1.00 for the SPCZ, the following results were obtained: SPCZ — 1.00, SAFR — 0.77, AUST — 0.73, SHT — 0.65, INDO — 0.69, NHT — 0.77, SACZ — 0.67, and OTHR — 0.46, where OTHR, SHT, and NHT represent the other (remaining) Southern Hemisphere tropical areas not accounted for by specified regions, the Southern Hemisphere total Tropics (0°–30°S), and the Northern Hemisphere total Tropics (0°–30°N). It is worth mentioning that the reliability of the $Q_i$-budget estimates was tested by Vincent et al. (1991a). They compared their precipitation values to those from island station and atoll reports, as well as
to those presented in some rainfall atlases, and concluded that the $Q_1$-budget technique is capable of providing mean monthly values over open oceanic areas that are consistent with observational data. Furthermore, in an earlier study (Miller and Vincent 1987), it was found that $Q_1$-budget estimates of precipitation in the SPCZ region were in good agreement with those derived using an IR satellite algorithm.

5. Quasi-periodic behavior

The location and intensity of the SPCZ (particularly the diagonal portion) have been observed to fluctuate on a variety of timescales ranging from synoptic to interannual [e.g., see Gruber (1972) for one of the earliest documentations]. In this rather wide spectra of temporal scales, the ones discussed in this paper, beginning with the shortest are 1) synoptic (few to several days); 2) intraseasonal (2–4 weeks and 30–60 days); 3) seasonal (several months); and 4) interannual [e.g., El Niño/Southern Oscillation (ENSO)]. A discussion of the seasonal/annual cycle was given in section 2, and a discussion of the synoptic-scale variability is the focus of section 6. In this section the intraseasonal and interannual oscillations are discussed. As stated above, intraseasonal fluctuations in the SPCZ appear to occur on two preferred timescales, 2–4 weeks and 30–60 days. The latter is often referred to as the Madden–Julian oscillation (MJO) after the pioneering work by Madden and Julian (1971, 1972). Kiladis and Weickmann (1992a,b) examined 5 years of filtered data in the Southern Hemisphere Tropics and higher latitudes for three distinct periods: 6–14, 14–30, 30–70 days. They found that the zonal portion of the SPCZ contained a pronounced summertime spectral peak in OLR within the MJO range at about 50 days, in agreement with several other authors (e.g., Lau and Chan 1985, 1988; Weickmann et al. 1985; Knutson and Weickmann 1987; Vincent et al. 1991b). They also found that the diagonal portion of the SPCZ exhibited a significant peak near 18 days, which was captured in the 14–30 day band. More will be said concerning this band later; for the present, a discussion of the 30–60-day period is continued.

There is ample evidence that intense convective episodes in the SPCZ are out of phase with those in the Indian Ocean (e.g., Weickmann et al. 1985; Hurrell and Vincent 1990; Pedigo and Vincent 1990), and it appears that this dipole is modulated on MJO timescales. For example, Weickmann et al. (1985) used filtered OLR data to show the evolution and propagation of convective cloudiness around the global Tropics. Figure 17, reproduced from their results, shows that OLR anomalies over the Indian Ocean tend to be out of phase with those over the western to central Pacific Ocean (i.e., SPCZ region) on 28–72-day timescales. The results of Hurrell and Vincent (1990) and Pedigo and Vincent (1990) support the relationship shown in Fig.

17. These papers, however, examined only a portion of the 60-day SOP-1 period of FGGG; therefore, it was not possible for the authors to verify that their findings were related to an MJO type of cycle. Nonetheless, their results did show a shift of convective activity and corresponding circulation features from the SPCZ region in mid-January 1979 to the western Indian Ocean by early February. Figure 18, which shows the OLR patterns for two 2-week periods in January–February 1979, illustrates this shift. From 10 to 24 January, the SPCZ exhibited strong convection in the central Pacific, whereas in late January and early February, convective activity weakened as the SPCZ tried to re-establish itself nearer Australia. In contrast, the western Indian Ocean was essentially free of deep convection in the first period but became relatively active in the second. Hurrell and Vincent (1990) found that there was a persistent area of subtropical wind maxima to the south and east of the OLR minimum in the SPCZ region during mid-January. When maximum convective activity shifted to the Indian Ocean in late January, it also contained a corresponding subtropical jet to its south and east.

In the other study alluded to above, Pedigo and Vincent (1990) derived area- and time-averaged precipitation rates for regions similar to those in Fig. 16. They compared values computed as residuals from the $Q_1$- and $Q_2$-budget methods of Yanai et al. (1973) for two 15-day periods, 10–24 January 1979 and 28 January–11 February 1979. The first period is the same as, and the second one is nearly the same as, those illustrated in Fig. 18. Their results are given in Fig. 19 and show that the best agreement in precipitation rate estimates between the two methods occurs in the SPCZ and Indian Ocean regions. Furthermore, it is seen that values decreased (increased) substantially in the SPCZ (IND O.) regions from period 1 to period 2. Taken together with other results cited above, this sequence of events suggests that the intraseasonal MJO may have had an impact on modulating the SPCZ.
In still another study, von Storch and Xu (1990) used a statistical approach, known as principal oscillation pattern (POP) analysis, to investigate the influence of the MJO in the tropical atmosphere. They found that a POP, corresponding to a 30–60-day wave, contained a marked annual cycle and accounted for 70% of the variance in the upper-troposphere velocity potential as it traversed the SPCZ. In this context, Vincent et al. (1991b) found a high correlation in the MJO band between velocity potential at 200 hPa and OLR along the zonal portion of the SPCZ in the summer of 1984/85. In the following summer, however, the correlation was considerably lower, showing that the velocity potential is not always a good indicator of SPCZ convection.

**Fig. 19.** Histogram of precipitation rate estimates (mm h⁻¹) for selected regions in the Southern Hemisphere Tropics. Also shown are the global values for the Northern and Southern Hemisphere Tropics (extracted from Pedigo and Vincent 1990).
In a study of the quasi periodicity of the motion of the SPCZ cloud band, Streten (1978) found a preferred periodicity in the east–west movement of the eastern portion of the band (between 20° and 40°S) of about 25 days. He used 5-day averages of satellite imagery from 1968 to 1971, and noted that the cloud band would undergo several 5-day periods of eastward movement followed by a rather abrupt westward movement back to its original position. Figure 20 illustrates these eastward propagations and recurring westward reversals. Note that 30% of the reversals occur near 30°S with a period of about 25 days. Streten (1973) previously suggested that the eastern sector of the SPCZ cloud band was related to midlatitude trough intrusions into the subtropical South Pacific. The same conclusion was reached by several other authors (e.g., Webster and Curtin 1975; Trenberth 1976, 1991a; Streten and Zillman 1984; Kiladis and Weickmann 1992b).

We now turn our attention to interannual variability of the SPCZ. The primary circulation features of interest here are El Niño, La Niña, and the SO. The relationship between these phenomena and the SPCZ has been discussed in detail by several authors (e.g., Trenberth 1976, 1991a; Rasmusson and Carpenter 1982; Trenberth and Shea 1987; van Loon and Shea 1987; Meehl 1987; Philander 1989). Although El Niño and the SO do not always occur in conjunction with one another (Trenberth and Shea 1987), they usually do and are referred to as ENSO. In general, during an El Niño (warm) event, the SO is negative (i.e., surface pressures are lower than normal over the South Pacific and higher than normal over northern Australia). Figure 21, which appears in Rasmussen (1985) and Trenberth and Shea (1987), shows a composite of the correlations of annual mean sea level pressures with those at Darwin. Note that the average position of the diagonal portion of the SPCZ (dashed line) is about midway between the centers of positive and negative action. This implies that the SPCZ is the focal point for ENSO events. That is, during an El Niño, the SPCZ is generally north and east of its average position, and the pressures are lower over the central South Pacific. Figure 22 shows the MSLP distribution for January 1987, which was in the middle of an El Niño period. By comparing this pattern with the January climatology shown in Fig. 2, it is clearly seen that the pressure during El Niño is slightly lower (considerably higher) than normal over the tropical central South Pacific (northern Australia) and that the SPCZ surface trough is northeast of its average position. During a La Niña (non–El Niño or cold) event, the SO is usually positive and the SPCZ lies south and west of its average position. Figure 23 shows the MSLP map for January 1989, which was in a La Niña period. Note the higher (slightly lower) pressures over the central Pacific (northern Australia) and the more southwestern position of the SPCZ surface trough.

Another example of the changing circulation features that can occur in the SPCZ region during El Niño and La Niña events is illustrated in Fig. 24. This shows departures of the zonal wind component at 200 hPa from their climatological mean for the 3-month seasons of March–May 1987 (an El Niño) and December 1988–February 1989 (a La Niña). It is seen that an anomalously strong upper-level anticyclonic (cyclonic) circulation occurs over the central South Pacific during El Niño (La Niña). These patterns are compatible with the observed fact that more (less) convective outflow takes place over the South Pacific in an El Niño (La Niña). Figure 25, extracted from Meehl (1987), provides a convenient summary of the features associated with the two extremes of ENSO events described above. The strong annual cycle corresponds to a La Niña, while the weak annual cycle is representative of an El Niño.
Rasmusson and Carpenter (1982) examined the changing characteristics of SST, MSLP, and precipitation anomalies during six El Niño events. They gave a detailed description of the sequence of these variables for each of the five phases (antecedent, onset, peak, transition, and mature) of El Niño, based on composited results. They noted that their analyses should be interpreted with caution and that they may be biased by the stronger of the six events. Nevertheless, they comment that their results are consistent with a number of statistical and case studies by other authors. Of importance to this paper is the fact that they found a transition in the pattern of variables and a shift in the position of the SPCZ during each of the El Niños, which are compatible with the results discussed above.

6. Synoptic-scale features

Because the SPCZ is influenced both by tropical heating, moisture convergence, and extratropical wave activity, it is a region where synoptic-scale circulation systems frequently are spawned. The zonal portion of the SPCZ is where tropical cyclones are often observed, particularly during the Australian summer monsoon season. In the diagonal portion of the SPCZ, between 20° and 40°S, a variety of synoptic-scale features are present and appear to be responsible for the maintenance of the cloud band. Thus, the focus here will be on those features that include cyclones, anticyclones, wave disturbances, fronts, upper-air troughs and ridges, and jet streaks, as well as some of the interactions that occur among these phenomena. Several early investigations, based on 1957–58 International Geophysical Year data (Taljaard 1964, 1965, 1967; Taljaard and van Loon 1962, 1963) and satellite imagery (Troup and Streten 1972; Streten and Troup 1973; Streten 1975), provided a climatology of cyclones and anticyclones for the Southern Hemisphere. These studies illustrated
Figure 24. Anomalous departures from 1985–90 average of the zonal wind component (m s$^{-1}$) at 200 hPa for (a) March–May 1987 and (b) December 1988–February 1989.

Figure 25. Schematic diagram illustrating processes that evolve during (a) a strong annual cycle—also can accompany an extreme cold event or La Niña, and (b) a weak annual cycle—also can accompany an extreme warm event or El Niño (extracted from Meehl 1987).

that a large number of cyclones develop and propagate southeastward over the South Pacific Ocean (e.g., Streten and Troup 1973) in what is now known as the SPCZ. For the most part, however, detailed analyses of the flow features associated with these cyclones have been lacking, primarily due to sparsity of observational data. One exception to this occurred during SOP-1, FGGE, when ample data were available in the SPCZ region to provide an analysis of cyclone activity and related synoptic-scale features (Vincent 1982, 1985). The author and his colleagues authored several papers that were devoted to diagnosing these features during SOP-1. Their results are summarized herein. Before proceeding to a discussion of their papers, however, it is important to mention that Trenberth (1991b) wrote an excellent paper on storm tracks in the Southern Hemisphere. His primary focus was on storms at higher latitudes and he offered minimal reference to SPCZ storms. Furthermore, as stated by Streten and Troup (1973) and many other authors, cyclonic disturbances in the South Pacific have a large variability both in time and space. Perhaps this is why the storms studied by Trenberth did not provide a strong signal in the SPCZ region.

Vincent (1985) performed a diagnosis of the life cycles of three cyclones in the SPCZ that occurred from 10 to 17 January 1979. During this period, the SPCZ and its cloud band were quasi-stationary and conditions were favorable for cyclone development (Huang and Vincent 1983). Shortly afterward, however, major changes took place in the large-scale circulation pattern across the Pacific, and the SPCZ shifted westward (19–24 January) and weakened considerably (25–27 January). Figure 26 shows averages of the MSLP and OLR $\approx 225$ W m$^{-2}$ for the 10–18, 19–24, and 25–27 January 1979 periods. The change in the pattern between the first two periods occurred on synoptic timescales and was due to a steady buildup of high pressure in the eastern Pacific. The central pressure rose from 1015 hPa on 18 January to 1027 hPa on 23 January. A similar, but more dramatic change occurred between the latter two periods in the central South Pacific (near...
160°W) and was due to a cold-air outbreak from mid-latitudes. There, the pressure rose from 1017 hPa on 22 January to a plateau value of almost 1030 hPa from 25 to 27 January. These features are seen in Fig. 27, which shows a time series of twice-daily central pressures of the two high pressure areas. Thus, as noted earlier, changes in the location and strength of the diagonal portion of the SPCZ may be related to variations in the eastern Pacific high, as well as to intrusions of polar air into the subtropics near the date line.

Returning to Vincent’s (1985) study, the tracks of the three cyclones are shown in Fig. 28. It is seen that one cyclone remained in the zonal portion of the SPCZ, while the other two propagated southeastward along the diagonal portion. The track of each cyclone seems to be influenced by the upper-tropospheric flow, as indicated by the daily maps of 200-hPa streamlines and isolats shown in Fig. 29. Note that L2, which deepened as it propagated toward midlatitudes (Fig. 28), was located in the exit region of a transient jet streak, whereas L3, which weakened considerably as it propagated poleward, was located in the entrance region of the same jet streak. Vincent also showed that L2 contained more convective activity and precipitation than L3. It is worth noting that these three cyclonic disturbances were all active on 12 January, which was one of the dates quoted by Davidson and Hendon (1989), in their paper referred regarding the origin of the SPCZ, that corresponded to a downstream strengthening of the South Pacific vortex.

An important finding in Vincent’s study was that L2 and L3 exhibited reasonably strong frontal characteristics as far equatorward as 27.5°S, even though it was midsummer (i.e., sun nearly overhead) and they were located over the open sea. Evidence of this is seen in Fig. 30, which shows a time–height section of winds and vorticity at a grid point near the island of Rapa (station 958 in Fig. 28), as well as the surface reports from Rapa. As the cyclones pass by this point, warm-(cold-) air advection occurs ahead of (behind) them, as indicated by the backing (veering) of the 1000–700-hPa winds. Both cyclones exhibit upper-tropospheric anticyclonic (cyclonic) vorticity ahead of (behind) their passage near Rapa. There is also enhanced cyclonic vorticity in the lower troposphere as each cyclone passes this location. The surface conditions at Rapa show increasing (decreasing) clouds and rain, and a wind shift as each cyclone approaches (departs).

Each of the features described above supports the general characteristic of the SPCZ alluded to in early sections of this paper, namely, that it is highly baroclinic. Robertson et al. (1989) examined the role of diabatic heating and other processes in maintaining this baroclinic zone and concluded that 1) a major balance existed between the frontogenetical contribution by differential diabatic heating and the opposing diabatic tilting processes, and 2) in contrast to midlatitude cyclones, the adiabatic contributions from the deformation and tilting terms were of lesser importance. Their findings were compatible with the eddy energy budget results of Hurrell and Vincent (1987) discussed in section 4.

The study by Robertson et al. (1989), together with those by Hurrell and Vincent (1990, 1991), address a very important issue with regard to forcing mechanisms of synoptic-scale systems that occur in the diagonal portion of the SPCZ. They state that it was difficult for them to say whether outflow from the cyclone’s diabatic heating field caused an enhancement of the upper-level winds (and, thus, established a baroclinic zone) or whether the jet streaks set up a baroclinic zone that was favorable for cyclogenesis and the attendant diabatic heating. It appears, therefore, that a complicated

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**Fig. 26.** Average sea level pressure (mb) for (a) 10–18 January, (b) 19–24 January, and (c) 24–27 January 1979, together with OLR \(\leq 225\) W m\(^{-2}\) (shaded). This figure was compiled from diagrams presented by Huang and Vincent (1983).
two-way interaction between heating and wind fields exists in the SPCZ. Furthermore, as was suggested in section 3, the cause of the SPCZ jet streaks is not well understood but is most likely due to a combination of tropical and midlatitude influences.

7. Concluding remarks and challenging problems

In this paper, an attempt has been made to review some of the knowledge concerning the SPCZ. Topics discussed were the structure and characteristics of the SPCZ; possible causes of its location, origin, and maintenance; its role in global-scale circulations, some observations concerning quasi-periodic fluctuations in its location and strength; and a few of the synoptic-scale features that occur within its domain. In summary, it was suggested that the processes that maintain and change the zonal (tropical) portion of the SPCZ are most likely different from those that are responsible for the diagonal (subtropical and lower midlatitude) portion. In this regard, several theories and hypotheses were discussed. It was documented that the SPCZ is an important part of, and often contributes to and interacts with, circulation features across the Pacific Ocean, both in the Tropics and extratropics. Furthermore, it appears to play a role in the cross-equatorial flow. It was also shown that interactions between the SPCZ and other locations occur on a variety of timescales from synoptic to interannual. It appears, therefore, that a better understanding of the SPCZ would lead to improvements in weather forecasting and climate prediction.

There are a number of challenging problems, some of which, if solved, could enhance our knowledge of the SPCZ. For example, there is still much that needs to be learned about the relative importance of processes and mechanisms that are responsible for the location and strength of the SPCZ and its circulation features. In the tropical (zonal) portion, the roles of warm SSTs, SST gradients and latent heat release need to be better understood. In this regard, one of the primary issues is related to the following question: How does the SPCZ respond to, and interact with, low-frequency phenomena such as the intraseasonal oscillation and ENSO events? One of the main contributors to this paper, Dr. Kevin Trenberth, suggested that a good climatology of the SPCZ and changes in ENSO would be useful. As discussed in the text, the SPCZ generally lies north and east of its “average” position during an El Niño. It was pointed out by Vincent (1982), however, that from 10 to 18 January 1979 the SPCZ was located north and east of its normal position, even though this was not an El Niño period. On the other hand, Huang and Vincent (1988) and Hurrell and Vincent (1990) speculated that the SPCZ region was under the influence of the convectively active part of an intraseasonal oscillation during 10–18 January. Thus, as indicated above, a better understanding of the relative roles of phenomena on low-frequency timescales needs to be achieved.

In the subtropical and lower midlatitude (diagonal) portion of the SPCZ, more knowledge is required concerning the importance of tropical versus higher-lat...
tude influences. In this regard, most of the evidence provided in this paper came from analyses during SOP-1, FGGE. Further studies need to be conducted that address the following questions: 1) What are the respective roles of tropical heat sources, the subtropical high over the eastern Pacific, and intrusions of cold polar air into the western and central subtropical Pacific, with regard to changing the circulation features within the SPCZ? and 2) Is there a relationship or teleconnection between the second and third factors in question? It would also be useful to have a better understanding of the interactions between diabatic (and adiabatic) processes in a convective disturbance and the upper-tropospheric jet that usually accompanies the disturbance.

Another problem worthy of consideration is the link between the circulation patterns over the Indian Ocean and the SPCZ. As mentioned in the text, there appears to be an out-of-phase relation between these two regions such that when one is convectively active the other is not. This relationship, which is generally attributed to intraseasonal oscillations, is but one of several that can alter the location and strength of the east-west circulation across the Indian-Pacific Ocean tropical corridor. In this context, it appears that the key location to a better understanding resides in the warm pool region of the western Pacific. This region undoubtedly makes major contributions to, and interacts with, the SPCZ and other circulation features in its vicinity (e.g., Australian monsoon). It is believed, therefore, that results from recent field programs, such as the Australian Monsoon Experiment and the Tropical Oceans Global Atmosphere Coupled Ocean–Atmo-
sphere Response Experiment, will provide answers to some of the questions and problems posed above.

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