# Origin of the South Pacific Convergence Zone

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## ABSTRACT

The importance of the presence of South America and Australia to the existence and orientation of the South Pacific Convergence Zone (SPCZ) during January is explored using the ECMWF T21 model. Each of the continents is removed from the model and replaced with an ocean surface, and the resulting precipitation and circulation associated with the SPCZ are then compared to a perpetual January control run. Results show that the presence of South America and the equatorial Pacific upwelling zone does not appear to be crucial to the SPCZ, but that the removal of Australia destroys the southern monsoon and substantially weakens the western part of the SPCZ. This suggests that the northwest-southeast orientation of the SPCZ during southern summer is more dependent on interactions with the midlatitude westerlies over the South Pacific than on the distribution of sea surface temperature and land over the Southern Hemisphere.

## 1. Introduction

The South Pacific Convergence Zone (SPCZ) is an important feature of the summertime circulation of the Southern Hemisphere. It is marked by a region of surface convergence extending in a northwest–southeast direction from the region of New Guinea to around 30°S, 120°W (Fig. 1). Although described by Bergeron (1930) by means of surface wind, cloud, and rainfall observations, and conspicuous in early ocean climate atlases, the SPCZ did not draw much attention until the 1960s, when satellite cloud imagery became available (Hubert 1961). Much of what is now known about the SPCZ has since been obtained from detailed study of satellite cloudiness (e.g., Streten 1973, 1975, 1978; Streten and Troup 1973), since the observational network is sparse over the central and eastern South Pacific. From such studies it is apparent that the SPCZ changes from a true tropical convergence zone in its western portion to a region with mixed tropical and extratropical characteristics at its eastern margin (van Loon 1965; Trenberth 1976). Recent improvements in data quality over this area, and in particular the availability of FGGE data from 1979, have made it possible to examine the SPCZ in terms of its energetics (Huang and Vincent 1985, 1988a, 1988b) and also from the standpoint of case studies of selected synoptic situations (Vincent 1982, 1985). The strong link between the tropics and extratropics in the region of the SPCZ may be responsible for the observed poleward progression of circulation anomalies in this sector (Trenberth 1981; Meehl 1988). A detailed description of the climatology of the SPCZ with extensive references can be found in Streten and Zillman (1984).

The existence of the SPCZ has often been assumed to be the result of the convergence of northeasterly trade winds from the South Pacific high and southeasterlies ahead of migratory anticyclones from the Australian region (Streten and Zillman 1984). The rather unusual northwest–southeast orientation of the convergence zone is generally thought to be related to the distribution of sea surface temperature (SST), with relatively cold water in the eastern tropical and subtropical South Pacific viewed as the primary reason for the lack of convection in that region. This SST distribution is generated by strong upwelling and equatorward advection of cold water to the west of South America.

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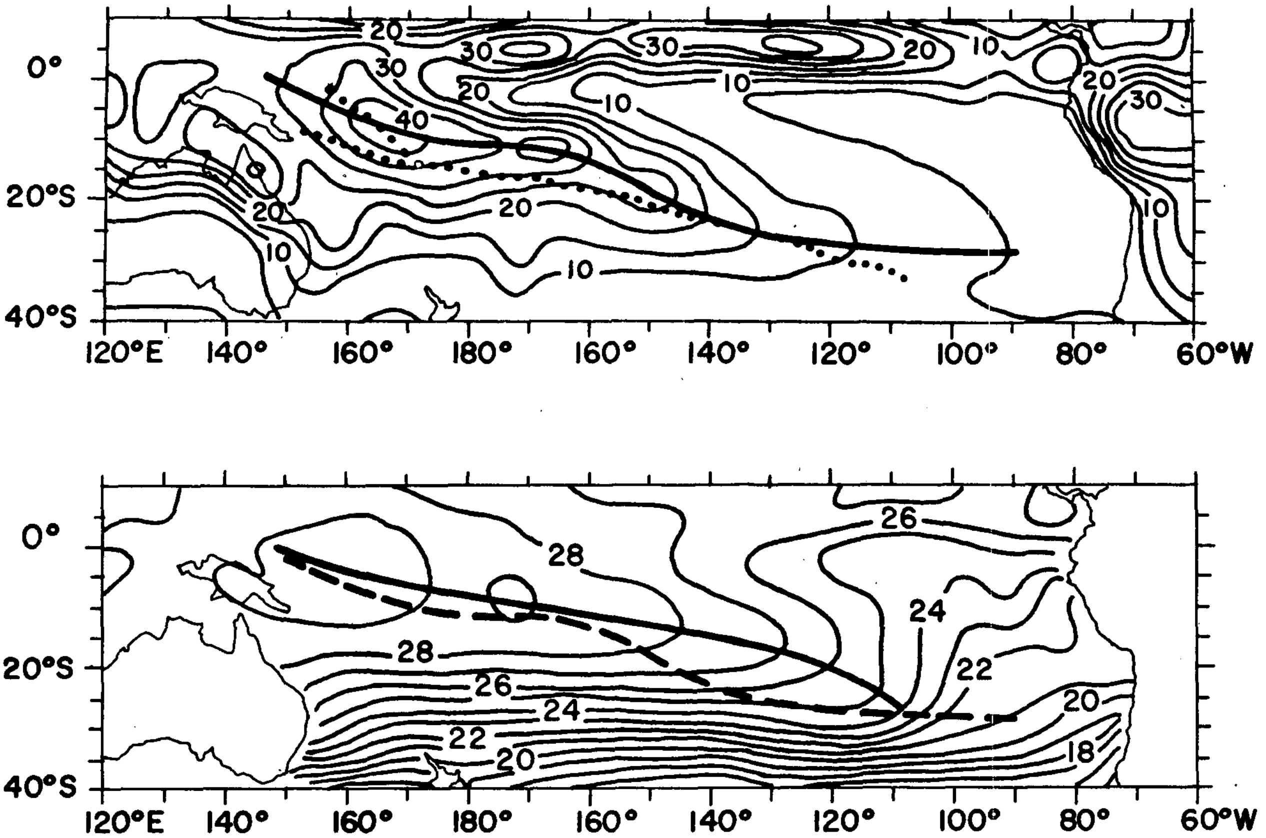

FIG. 1. (a) Mean January precipitation (cm/month) for the period 1950–79, from Shea (1986). Contour interval is 5 cm/month. Also shown as a solid line is the axis of highest precipitation, and as a dotted line the axis of maximum surface wind convergence from Legler and O'Brien (1984) for the period 1961–80. (b) Mean January SST (°C) for the period 1950–79, from Shea (1986). Contour interval is 1°C. Solid line depicts the axis of maximum SST, and the dashed line the axis of highest precipitation, taken from (a).

Evidence presented in Fig. 1, however, does not support the notion that the orientation of the SPCZ is related in any simple way to SST. In Fig. 1a it is seen that the surface convergence maximum associated with the SPCZ lies to the south of the axis of maximum precipitation, typical of tropical convergence zones (see Riehl 1979). In turn, the maximum precipitation lies to the south of the axis of maximum SST in Fig. 1b, especially in the central South Pacific. One can, for example, trace the 28°C SST isopleth from a region of 10 cm/month precipitation just south of the equator at 160°W, to a region of 30 cm/month precipitation to the west of Fiji near 18°S, 175°E. Thus, while the tropical sector of the SPCZ is certainly anchored to the western Pacific warm pool, the central and eastern portion is not forced principally by the underlying SST but is controlled to a large extent by interactions with the higher latitude circulation. In this sense the large meridional SST *gradient* and associated upper level westerlies in this sector may be more important to the SPCZ than the actual SST itself.

This study is an investigation of the nature of the SPCZ through the use of general circulation model (GCM) experiments. We used the T21 ECMWF model in our experiments, which simulates reasonably well the main climatological features of the tropical atmosphere, including the SPCZ and the North Pacific Intertropical Convergence Zone (ITCZ). In a previous study using the same model (Storch et al. 1988), it was shown that the strength of the model SPCZ is critically dependent on local SST over the western tropical South Pacific. The main question we wish to address in the present study is to what extent the position and strength of the SPCZ are due to the distribution of continents and SST over the Southern Hemisphere. Three experiments were conducted by removing South America, then Australia, and then both continents from the model, and the results compared with a model climatology from a control run. Since the SPCZ is best developed in southern summer, we integrated the model in a perpetual January mode. The details of the experiments and the statistical procedure, called *recurrence analysis,* used to evaluate the differences between the various experiments are explained in section 2. The results of the experiments are presented in section 3, followed by a discussion in section 4.

## 2. Experimental design

### *a. Description of the model*

The model used for the experiments is a low resolution version of an operational forecast GCM developed at the European Centre for Medium Range Weather Forecasts (ECMWF). This model has already been described in detail elsewhere (see Fischer 1987; Storch 1988), and so only a brief summary is given here.

The model is global, with 15 layers in the vertical and with a horizontal spectral representation up to zonal wavenumber 21 (T21), giving a horizontal resolution of 5.625° × 5.625°. Deep convection is parameterized according to the Kuo scheme (Kuo 1974), and precipitation may also occur due to large-scale uplift. Input into the model is in the form of a lower boundary condition of SST over the oceans. Sea ice is specified according to a climatological mean extent. The surface temperature over land is a prognostic variable; that is, it is predicted from the surface heat balance equation. In our experiments, we have further modified the boundary conditions by removing land surfaces, replacing them with a sea surface.

### *b. Control experiment*

Since we are interested in changes in the SPCZ with varying boundary conditions during southern summer, it is important to verify first whether the SPCZ is well represented in the model control run. For this purpose we have used a perpetual January run of the model, using the long-term mean distribution of SST shown in Fig. 2a. These SST's represent a 1950–79 climatology from ship data in the Comprehensive Ocean-Atmosphere Data Set (COADS; see Woodruff et al. 1987). The model was run with these unvarying boundary conditions for 12 model months, and the mean fields derived from these runs are used to define the model "climatology."

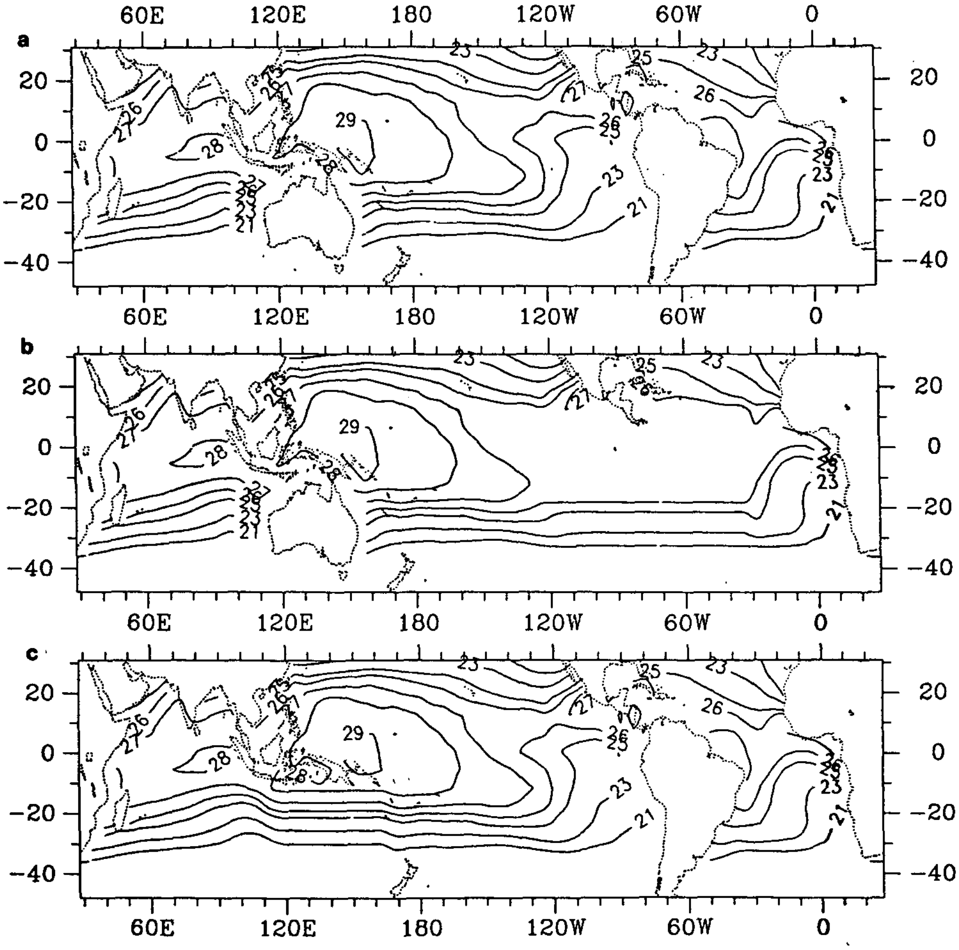

FIG. 2. January sea surface temperature (°C) used as boundary conditions for the (a) control run, (b) SAOUT run, (c) AUOUT run.

Figure 3b shows the mean total January precipitation from the control run from 30°N to 45°S. Shown for comparison in Fig. 3a is a map of the mean observed precipitation for the same region taken from Shea (1986). The intensity of precipitation in the model is generally too low, especially over Indonesia, but the patterns are adequately simulated with three major convective regions over Africa, South America, and the western Pacific. The SPCZ in the model is shifted to the southwest compared to observations, but nev-

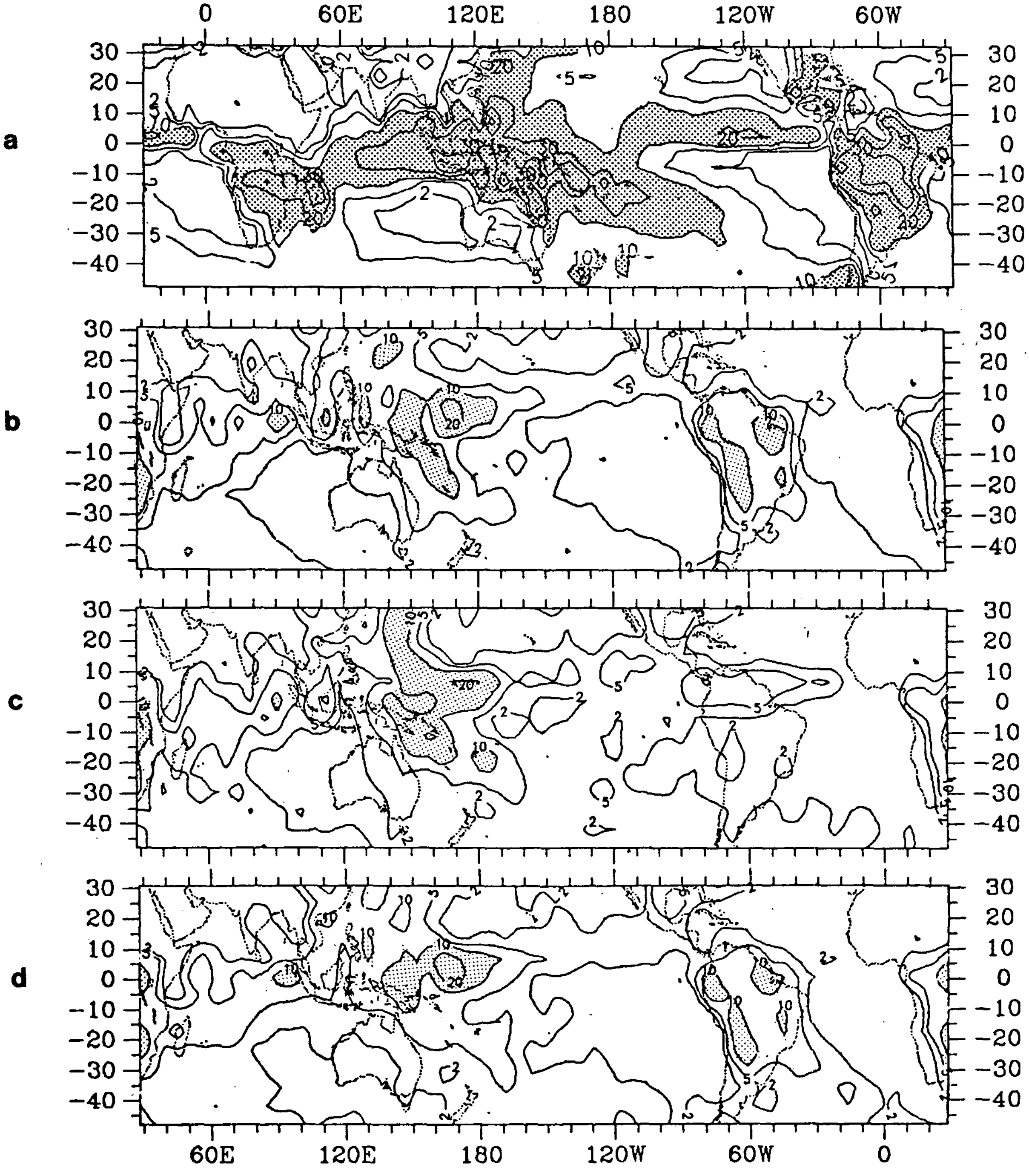

FIG. 3. Mean January precipitation (mm/month). (a) observed (from Shea 1986), (b) control experiment, (c) SAOUT experiment, (d) AUOUT experiment. Areas with more than 10 cm/month are stippled.

ertheless has the proper orientation as a southeastward extension of the southern monsoon region into the South Pacific. The "dry zones" of the southeastern Pacific and Atlantic oceans are also reasonably well reproduced. Further discussion of the model precipitation climatology can be found in Kiladis (1988).

The model global sea level pressure (SLP) field is shown in Fig. 4b and the observed January field (from Shea 1986) in Fig. 4a. The model Southern Hemisphere is dominated by three subtropical ridges over the oceans and by heat lows over the land regions of Africa, Australia, and South America. Apart from an underestimate of the strength of the subtropical highs, the agreement between the modeled SLP climatology and the observed is quite good.

### *c. Anomaly experiments*

Three model experiments were designed to test the sensitivity of the SPCZ to continental and SST distribution. In the first experiment, called SAOUT, South America was removed from the model. Since the relatively low SST along the central and eastern equatorial Pacific and coast of South America is directly related to the presence of the continent, the climatological January SST used in the control run (Fig. 2a) was replaced by the SST distribution shown in Fig. 2b. Note that we have replaced the upwelling zone of the eastern Pacific with a more zonally oriented SST distribution by extending the isotherms from the western South Pacific to the western South Atlantic, where similar SSTs exist at the same latitudes in observed data. While there is, of course, no way of knowing whether this SST distribution would prevail if South America didn't exist, we think that a zonal orientation is the most reasonable first guess, and free from the risk of adding arbitrary detail.

In the second experiment, designated AUOUT, we have retained South America but removed Australia, using the SST distribution shown in Fig. 2c. In the third experiment, called BOUT, both continents were removed, and the boundary conditions (not shown) are specified by combining the SST distributions of Figs. 2b and 2c. The model was run for eight model months with each of the above boundary conditions, and the resulting model rainfall and circulation were then compared both with the control run and with observed climatological fields during January.

### *d. Recurrence analysis*

We use the notion of univariate *recurrence analysis* introduced by Storch and Zwiers (1988). An anomaly experiment $X$ is said to be (at least) $(p, q)$-recurrent compared to a control experiment $G$ if

$$P(X > Y_p) > q \qquad (1)$$

where $P(\cdot)$ denotes the probability that the statement in the parenthesis is true, and $Y_p$ is the $p$-quantile of the control experiment $G$, i.e., $P(G > Y_p) > p$. In this study we use $p = 50\%$ and $q = 80\%$ or 20%. The random variables $X$ and $G$ are January means of precipitation or sea level pressure. Then, (1) states that the probability of observing a January mean in the experimental run larger than the long-term control January mean is at least 80% (or at most 20%). In that case we will call the response *recurrent.*

Whether a response is recurrent or not may be subject to a statistical test. We use a nonparametric test (Storch and Zwiers 1988). It operates with a few discrete risks only, which explains the unusual level of 6.25% used for statistical significance in this paper. If the response at a certain gridpoint passes the test, it is said to be *significantly recurrent.* In order to obtain an ensemble of statistically independent samples, every second January mean is deleted from the total dataset. The control ensemble thus consists of 6 samples and the anomaly ensembles of 4 samples each.

## 3. Experimental results

### *a. South America Out (SAOUT)*

The mean rainfall pattern for the SAOUT run is shown in Fig. 3c, and the difference between SAOUT rainfall and the control run (Fig. 3b) is shown in Fig. 5a. The SPCZ still retains its orientation and strength in the western Pacific, and is even a little stronger than in the control run, despite the presence of relatively high SST across the entire Pacific basin. The ITCZ appears little changed in the western Pacific, but now there is a distinct new ITCZ located just north of the equator in the region formerly occupied by South America. The Pacific dry zone shows a relatively large increase in precipitation, but is still much drier than regions farther north with similar SST in Fig. 2b.

Shown in Fig. 6a is a recurrence analysis of the rainfall in the anomaly runs compared to the control. A decrease in rainfall in the tropical and subtropical region formerly occupied by South America, and an increase in precipitation in the eastern Pacific, are significantly recurrent. Another small region of significantly increased precipitation occurs just north of the equator in the western Atlantic, reflecting the new ITCZ in that location. There is also a small area of significant precipitation change in the SPCZ region at about 20°S and the date line, but this occurs at only two gridpoints. It can be concluded, then, that precipitation in the SPCZ itself does not appear to be substantially affected by the removal of South America and the eastern Pacific upwelling region in the model.

The SLP field from the SAOUT run is shown in Fig. 4c, and the difference from the control run (Fig. 4b) in Fig. 7a. SAOUT essentially results in the merging of the South Pacific and South Atlantic highs into one

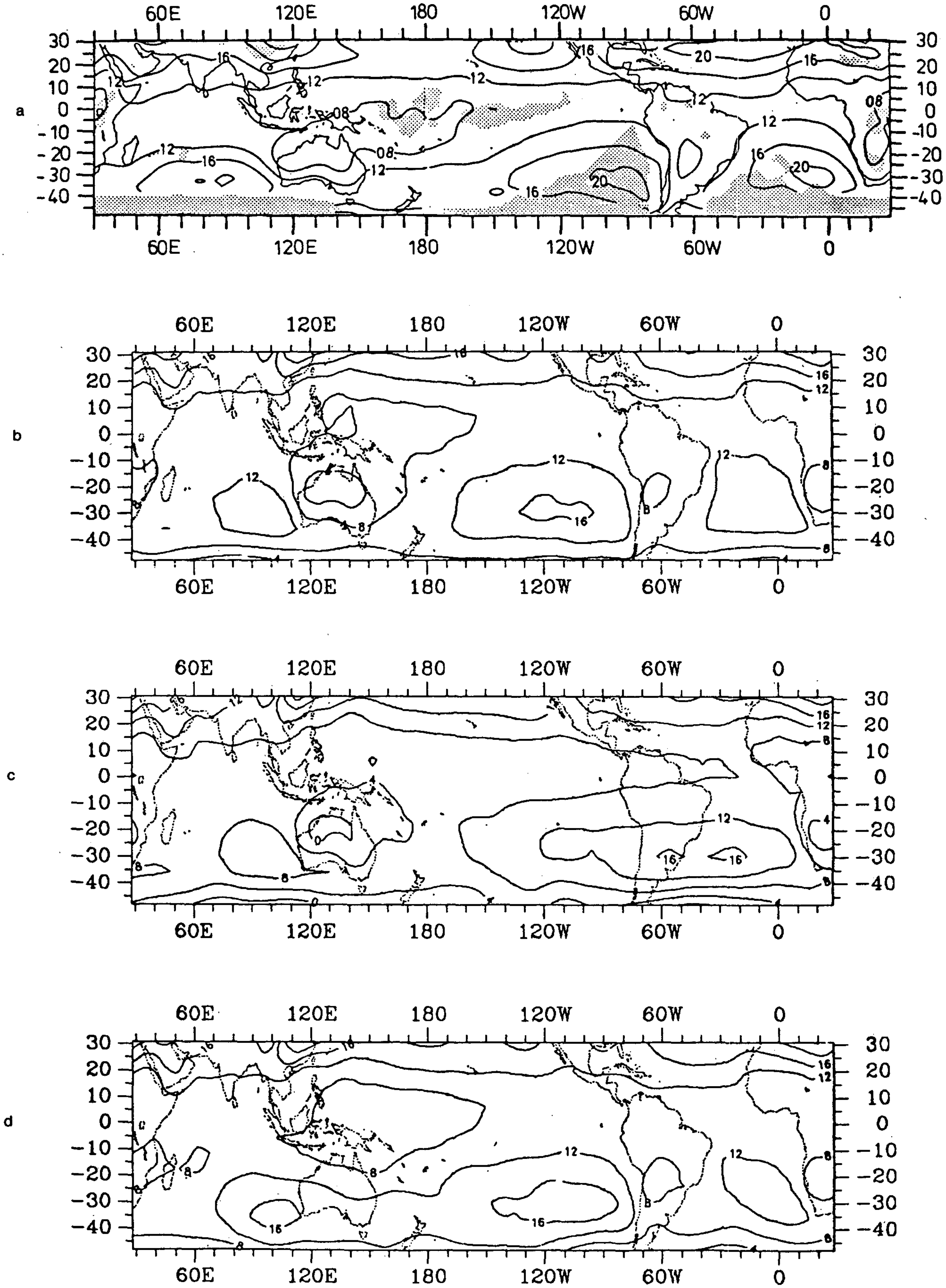

FIG. 4. Mean January sea level pressure (mb − 1000). (a) observed, (b) control experiment, (c) SAOUT experiment, (d) AUOUT experiment. Shading in (a) denotes regions with sparse data coverage.

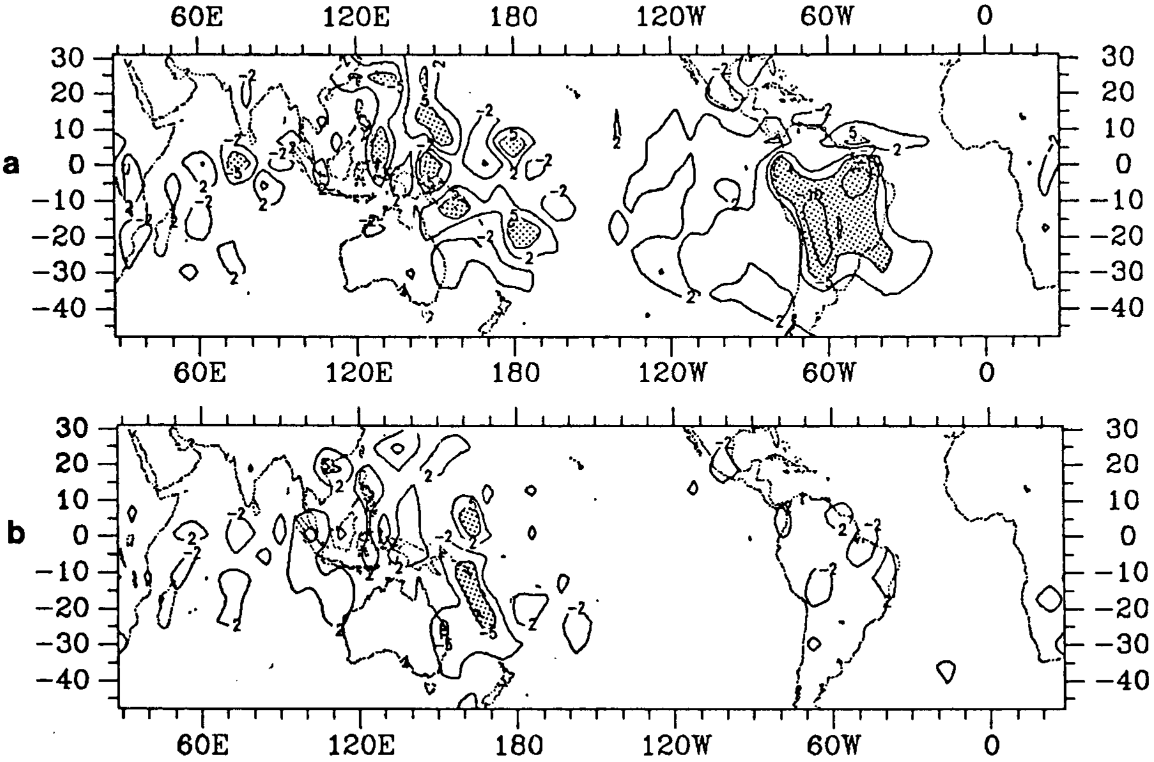

FIG. 5. Difference between the control experiment precipitation (mm/month) and the (a) SAOUT experiment (SAOUT − control), (b) AUOUT experiment (AUOUT − control). Areas with differences of more than 5 cm/month are stippled.

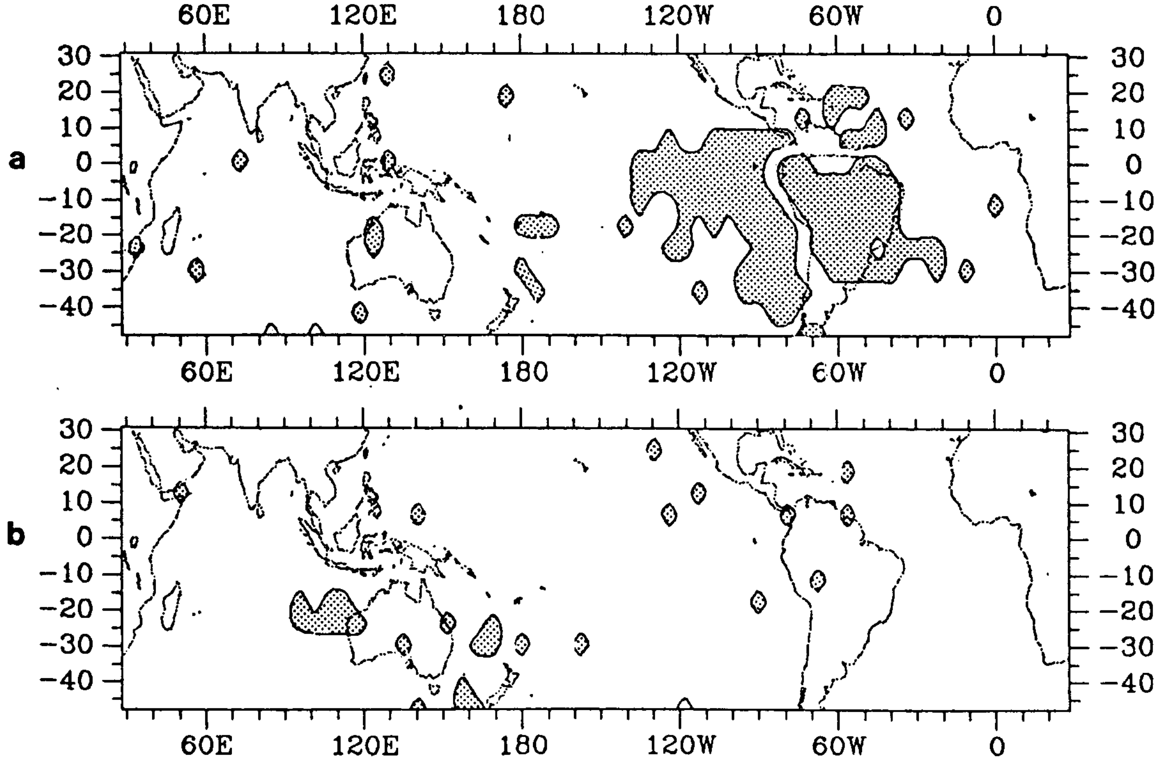

FIG. 6. Test of the statistical significance of the precipitation difference between the control and (a) SAOUT experiment, (b) AUOUT experiment. Zero contour has been omitted. Shading denotes regions where the signal is significantly recurrent.

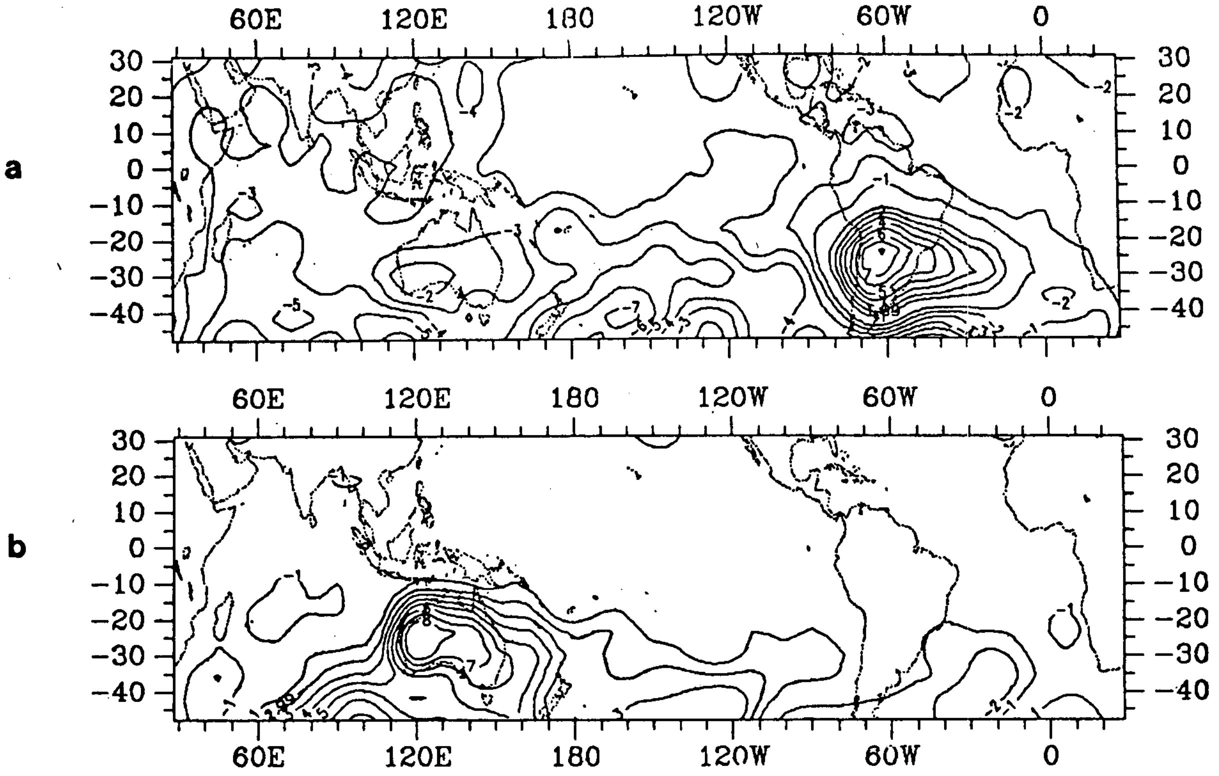

FIG. 7. As in Fig. 5, except for sea level pressure (mb) between the control experiment and (a) SAOUT experiment (SAOUT − control), (b) AUOUT experiment (AUOUT − control).

massive subtropical ridge. In addition, Fig. 8a shows a statistically significant reduction of SLP over the entire equatorial region, apparently compensated for by an increase in SLP over South America (as well as the Arctic, not shown). SLP is also substantially reduced compared to the control in the region of the western SPCZ and northern Australia, and this signal is significant in Fig. 8a. Nevertheless, a strong SLP *gradient* between the western and eastern South Pacific is maintained in this experiment, despite the zonal smoothing in the SST gradient; this preserves the tendency for surface convergence in the southwest Pacific.

The separate precipitation maximum between 90°W and 30°W is not only related to changes in the local surface boundary conditions, but also appears to be influenced by the convergence of stronger trade winds in the South Atlantic and in the former position of tropical South America. To the south of this convergence zone, the trade winds are divergent (not shown), as opposed to the convergent flow over the South American land mass in the control run.

### *b. Australia Out (AUOUT)*

Fields similar to those discussed above for SAOUT are given in Figs. 3–8 for AUOUT. As opposed to the SAOUT experiment, here we note a more substantial decrease in rainfall in the SPCZ (Figs. 3d and 5b). This signal, along with an increase in rainfall over the eastern tropical Indian Ocean, are the largest significantly recurrent precipitation responses associated with AUOUT (Fig. 6b). In Fig. 5b the signal in the SPCZ region amounts to a precipitation decrease over the entire Coral and Tasman seas, to the east of Australia. The divergence fields (not shown) indicate that the removal of Australia leads to a decrease in low-level convergence and upper level divergence over the western portion of the SPCZ.

If we examine the SLP and wind fields in the AUOUT experiment, it is apparent that the western portion of the SPCZ is intimately tied to the southern monsoon. In AUOUT, SLP shows the largest increase over the area of the former western Australian heat low (Fig. 7b), with the South Indian Ocean High now connecting across the region to the Pacific High (Fig. 4d). This is associated with a reversal of the surface westerlies observed over northern Australia in the control run to easterly trades implicit in Fig. 4d. Thus the removal of Australia eliminates the continental heating which produces the monsoon circulation over that region, resulting in easterlies and a decrease of precipitation extending into the region of the western SPCZ, where in the real world surface westerlies dominate at this time of year (Streten and Zillman 1984).

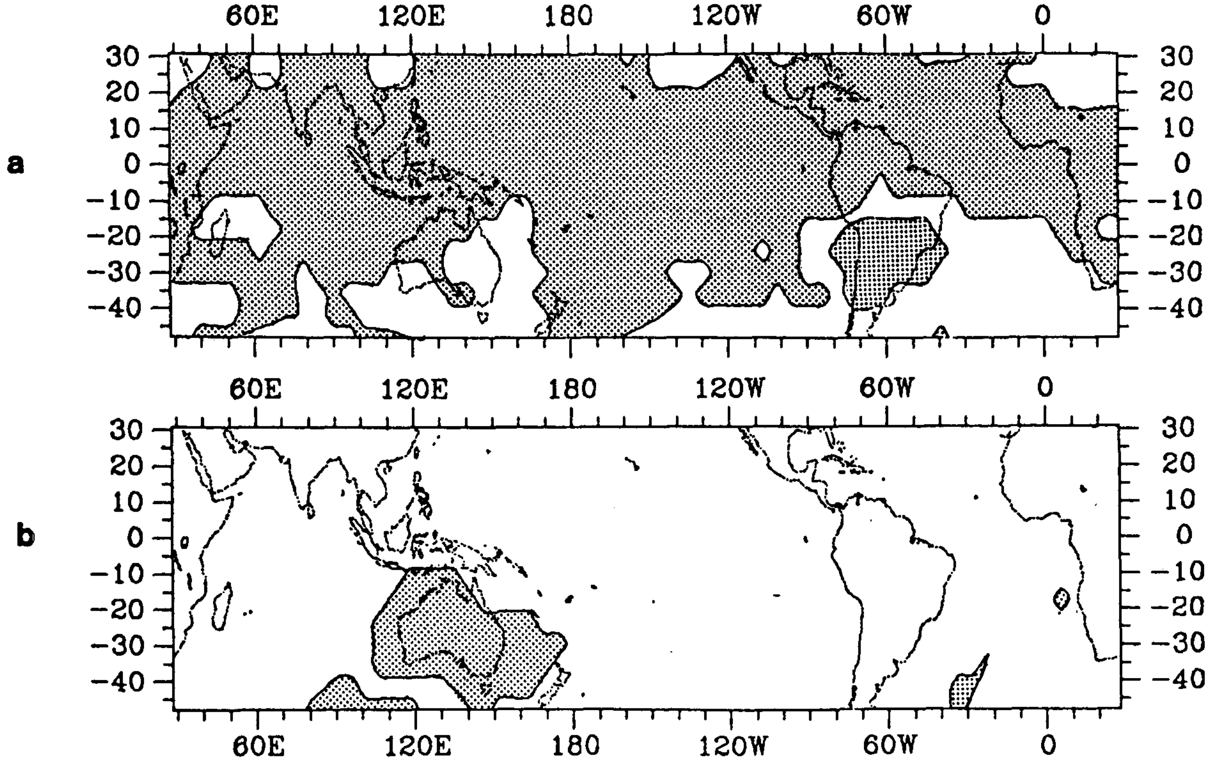

FIG. 8. As in Fig. 6, except for the difference in sea level pressure between the control experiment and (a) SAOUT experiment, (b) AUOUT experiment.

The precipitation response for both continents removed (BOUT, not shown) resembles the combined effect of removing each continent separately, and again shows a decrease in precipitation in the SPCZ with the largest responses over South America and the eastern Indian and Pacific oceans. The BOUT SLP field (not shown) is dominated by two extensive highs, one centered at about 30°S, 120°E, and the other centered at 30°S, 30°W. As in SAOUT, pressure is substantially decreased over large areas of the global tropics.

The effect of the changing boundary conditions on the large-scale divergent flow can be seen in Fig. 9, showing the mean velocity potential fields at 200 mb for the control and experiment runs. The control run (Fig. 9a) is dominated by the main velocity potential minimum of the western equatorial Pacific, and two minor minima centered on South America and Africa, features which closely resemble the observational field (not shown). Figure 9c establishes clearly that the removal of Australia has only the small local effect of moving the western Pacific velocity potential center slightly northward to the equator, whereas the removal of South America and the upwelling zone from the eastern Pacific creates one extensive Walker Circulation in both directions from the western Pacific to Africa (Fig. 9b). Thus the role of the convergent center over the eastern Pacific in Fig. 9a, which is related to the low SST there (e.g., Bjerknes 1969), has been taken over by the upwelling region off the west coast of Africa. This produces a global velocity potential field dominated by a substantially stronger wavenumber 1 pattern than in the control run or the observations.

## 4. Discussion

Based on the above results, the removal of South America, Australia, or both from the model has strong local effects, but only the removal of Australia significantly alters the strength of the SPCZ. Removing South America and the eastern Pacific upwelling region in the SAOUT experiment results in a precipitation decrease over the former central South American region and an increase over the eastern Pacific, along with the creation of a new ITCZ just north of the equator in that sector. SLP in SAOUT shows a decrease over a large region of the global tropics, with a merging of the South Pacific and South Atlantic highs. This is associated with strengthened trade winds across the tropical region formerly occupied by South America, and the convergence of these trades with the easterlies of the Northern Hemisphere in the new ITCZ. Although the surface circulation of SAOUT does show westerly anomalies in the region of the SPCZ, this signal is weak and of dubious statistical significance. What is more important is that the surface pressure gradient across the South Pacific and the associated surface

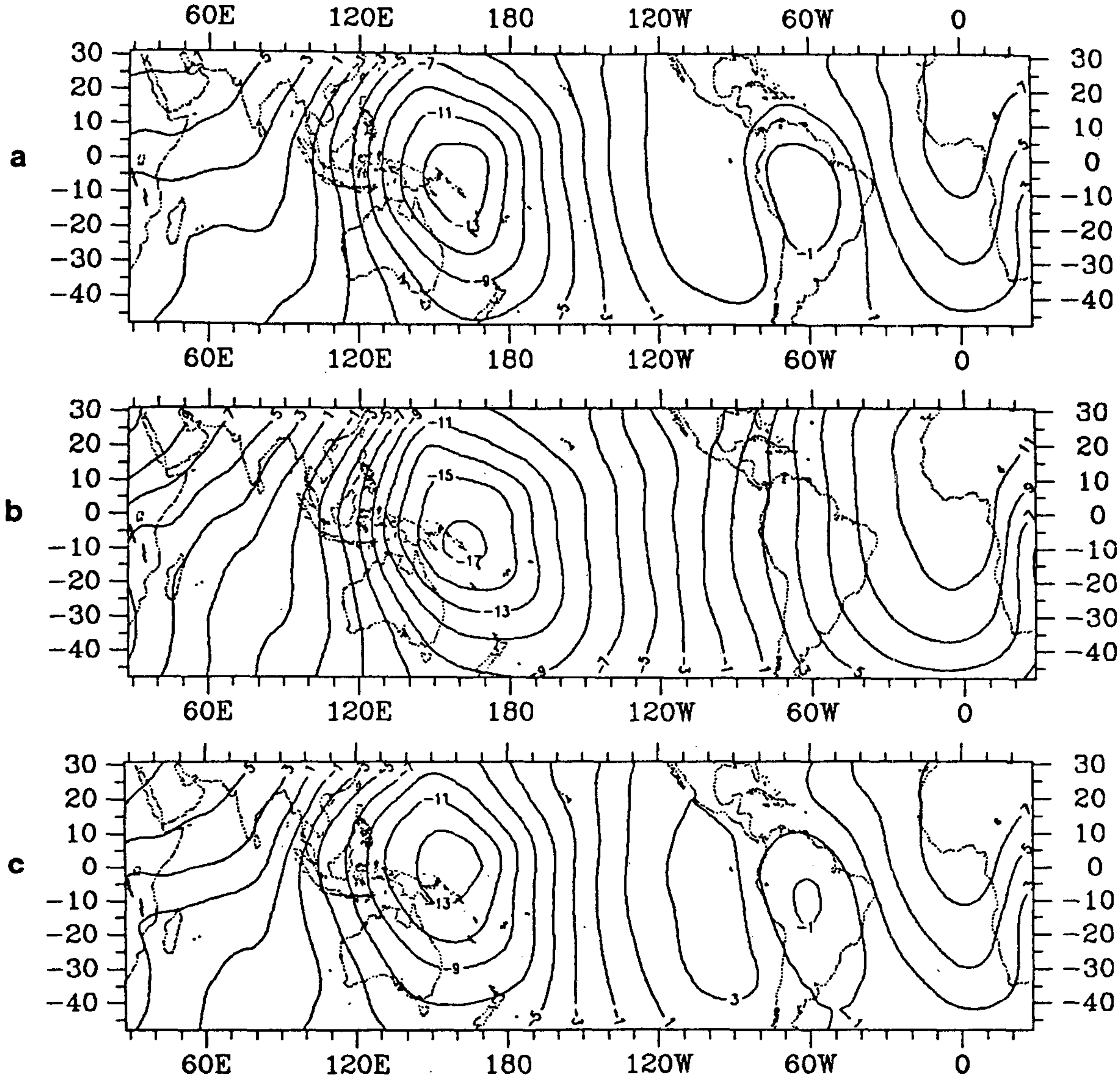

FIG. 9. Velocity potential at 200 mb ($10^6$ m$^2$ s$^{-1}$) from the (a) control experiment, (b) SAOUT experiment, (c) AUOUT experiment.

convergence in the SPCZ is maintained in this experiment, despite an overall decrease in SLP over the entire tropics.

The effect of removing Australia is to destroy the heat low and monsoon circulation over that continent, resulting in a strong easterly anomaly in that sector centered at about 15°S. This easterly anomaly is also present, although weaker, in the region of the SPCZ, resulting in less surface convergence and decreased precipitation. The largest effect is to increase the surface convergence to the west of Australia, resulting in substantially more precipitation there.

The above signals are all present in the BOUT runs. Huang and Vincent (1988b) speculate that generation of the SPCZ might be tied to the ocean–continent distribution, with the three continents and the high SST of the tropical South Pacific generating a predominantly wavenumber 4 pattern of convection in the summer Southern Hemisphere. Nevertheless, the SPCZ was still present, although substantially reduced in strength, even when both South America and Australia were removed from the model. While the existence of the tropical portion of the SPCZ is obviously tied to relatively high SST (Storch et al. 1988), the lack of a substantial change in the SPCZ in any of the runs, at least in terms of statistical significance, leads one to suspect that the orientation of the SPCZ is not due to the zonal gradient in SST across the South Pacific, but to interactions with the westerlies of the midlatitudes in that sector. This conclusion is strengthened by the fact that, despite the zonal orientation of SST across the Pacific in the SAOUT experiment, the SPCZ does not follow the region of highest SST, but maintains a northwest–southeast orientation.

We conclude that the orientation of the subtropical portion of the SPCZ must reflect "storm tracks" in the model emanating from the tropics. When a tropical convergence zone frequently interacts with transient troughs in the midlatitude westerlies, this interaction will be manifested as a "cloud band" extending into the midlatitudes. There is ample observational evidence that this is the case in the SPCZ (e.g., Streten and Zillman 1984; Vincent 1985). Given that the T21 model appears to simulate these processes realistically, we conclude that the southeastward orientation of the SPCZ is primarily due to its interactions with the midlatitude circulation rather than to the presence of continental boundaries or oceanic upwelling in the eastern South Pacific.

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