NOTES AND CORRESPONDENCE

Significance of the South Pacific Convergence Zone (SPCZ) in the Energy Budget of the Southern Hemisphere Tropics

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ABSTRACT

A modified set of FGGE Level III-b gridpoint analyses, originally produced by ECMWF, is used to diagnose the eddy energy budgets of four equal-area regions within the tropical Southern Hemisphere (0–30°S) during the SOP-1 period of 10–27 January 1979. Each region is approximately centered on a wave axis of maximum warm, rising air. Three of the four wave axes are tied to the continents of Africa, Australia, and South America, while the fourth coincides extremely well with the South Pacific Convergence Zone (SPCZ). Daily variations of the energy conversions are examined. In addition, time-averaged results of energy contents, conversions and boundary transports are compiled for a 15-day period, 10–24 January, when the SPCZ was most active.

Results show that the eddy kinetic energy (KE) exceeds the eddy available potential energy (AE) in all four regions, with that in the SPCZ being the largest. Of the conversion and boundary flux terms, only the conversion of AE to KE is significant. Again, the region containing the largest value is the SPCZ. The main flow of energy in each region appears to consist of a generation of AE by diabatic heating, a conversion of AE to KE by thermally-direct eddy circulations, and a dissipation of KE.

The relationships among the four subareas are investigated, primarily through evaluations of the boundary fluxes of KE. Results indicate that the only significant transport between regions is a flow of KE from the SPCZ region into the South American region. Thus, it appears likely that some of the KE from the SPCZ is helping to maintain the KE of the South American region and, in particular, the South Atlantic Convergence Zone (SACZ). These results seem to be in good agreement with the modeling results produced by the NASA Goddard Laboratory for Atmospheres (GLA) General Circulation Model.

1. Introduction

In a recent paper, Huang and Vincent (1985, hereafter referred to as HV) examined the significance of the South Pacific Convergence Zone (SPCZ) with regard to energy conversions in the Southern Hemisphere. Their period of study was 10–27 January 1979, which was part of the first Special Observing Period (SOP-1) of The Global Weather Experiment (FGGE). In studies which preceded HV, Vincent (1982) and Huang and Vincent (1983) found that the SPCZ played a dominant role in the general circulation of the tropical Southern Hemisphere from 10–24 January 1979. Subsequent to 24 January, they found that the SPCZ dissipated. By partitioning the energy conversions into zonal and eddy components, HV were able to establish that the baroclinic conversion (CE) of eddy available potential energy to eddy kinetic energy was the only significant conversion term in the Southern Hemisphere tropics (0°–30°S) during 10–24 January. Moreover, they found that standing eddies made the major contribution to CE. Likewise, the only significant conversion term in their SPCZ area (0°–30°S, 180°–120°W) was CE, again with the standing eddy contribution dominating. These results, which suggest that the SPCZ plays an important role in the production of eddy kinetic energy in the tropical Southern Hemisphere, provided the impetus for the present study.

Although the SPCZ was one of the dominant features of the tropical circulation, HV noted the presence of three additional regions of persistent convective activity, which were identified from maps of outgoing longwave radiation (OLR) profiles derived from NOAA polar-orbiting satellites. These three regions were observed over South America and the adjacent Atlantic, southern Africa, and the northern coast of Australia. Since rising warm air and sinking colder air are features generally recognized to be associated with convective systems, HV analyzed vertical p-velocities and temperatures at each level. The covariance between these variables was used to produce the values of CE noted earlier. An example of each of these variables at 500 mb has been extracted from their paper and is shown in Fig. 1, together with the geopotential height at 200 mb, for the latitude band, 20°–25°S. The latter variable is illustrated since rising warm air at mid-tropospheric levels frequently causes an inflation of upper-level height surfaces. It is seen that rising warm air and sinking colder air at 500 mb occur in conjunction with higher and lower upper-level heights, respectively. Moreover, four warm ridges are seen to exist. They are located over the three continents and the SPCZ. Although each of the ridges is not separated by precisely 90° of longitude, the spacing does suggest that wavenumber 4 may have made an important contribution

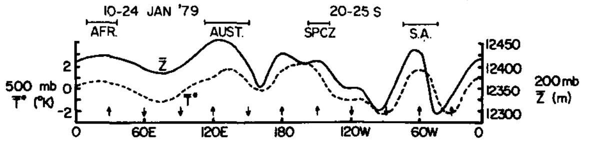

FIG. 1. Time-averaged longitudinal distribution of geopotential height ($\bar{z}$) at 200 mb in m (solid line) and temperature anomaly ($\bar{T}^*$) at 500 mb in K (dashed line) for the latitude band 20–25°S for 10–24 January 1979. Arrows at the bottom indicate the direction of vertical p-velocity ($\bar{\omega}$) at 500 mb.

to CE for this latitude band. A similar wave structure was observed in other 5° latitude bands between 15° and 30°S, but not much beyond those latitudes.

In order to quantitatively assess the importance of this apparent wavenumber 4, HV performed a spectral analysis of the data. By using the zonal Fourier analysis technique (for wavenumbers, n = 1–15) proposed by Saltzman (1957, 1970), they were able to establish that wavenumber 4 made the most significant contribution to the CE conversion during the period 10–24 January. It accounted for approximately 30 percent of the total (n = 1–15) conversion. Furthermore, for most of the period (from 11–22 January), the contribution by wavenumber 4 to the total value of CE was between 30 and 50 percent. After 22 January, when the SPCZ weakened and finally dissipated, the wavenumber 4 contribution was negligible.

In view of the results produced by HV, the present study conducts an in-depth investigation of the energetics, including boundary transports, of four equal-area tropical regions, each approximately centered on one of the wave axes of maximum warm, rising air noted above. Each region encompasses 90° of longitude and is bounded by the equator and 30°S. Hereafter, the four regions will be referred to as the SPCZ region (115°W–155°E), the Australian region (155°–65°E), the African region (65°E–25°W), and the South American region (25°–115°W). Since each region encompasses 90° of longitude and 30° of latitude, only the eddy contributions to the energy budget will be presented. The primary objective of the paper is to compare and contrast the intensities of the various components of the eddy energy cycle among the four regions. As will be seen, an important tie appears to exist between the SPCZ and South American regions. Hence, a second objective of the paper is to explore this relationship.

2. Methodology

a. Data sources

The dataset utilized in the present study is the same as that used by HV. It is a modified version of the Level III-b analyses provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). Details regarding the modifications are given by Vincent (1982). In brief, the data consist of daily values (average of 0000 and 1200 UTC) of the analyzed horizontal wind components (u, v), geopotential height (z), and mean sea level pressure (p_s), temperature (T) computed hydrostatically from the height field, and vertical p-velocities (ω) computed kinematically from the winds. An O'Brien (1970) mass adjustment scheme was applied to the vertical motions in which the vertically-integrated divergence was set to zero, with $\omega = 0$ at 1000 and 100 mb. In summary, all data utilized in this study are based on analyzed variables with a grid increment of 5° latitude and longitude.

b. Energy equations

With only minor modifications, the present study applies the eddy forms of the energy equations developed by Brennan and Vincent (1980). It is not appropriate to consider the zonal forms of energy for the present investigation because of the limited latitudinal and longitudinal extent of each of the four computational domains. By computing only the eddy forms of energy, the use of the approximate, rather than the exact, form of the energy equations provides sufficient accuracy. This is particularly true in the present case since the areas considered lie in the tropics where the approximate form of the equations is most accurate. Furthermore, as will be shown later, the generation of eddy available potential energy, which is the main term where a difference occurs between the exact and approximate forms of eddy energy, is not directly computed.

The eddy energy equations used here are given in symbolic form below. For a presentation and discussion of the full integral equations, the reader is referred to Brennan and Vincent (1980).

$$\mathrm{DAE} = \mathrm{CA} - \mathrm{CE} + \mathrm{GE} + \mathrm{BAE} \tag{1}$$

$$\mathrm{DKE} = -\mathrm{CK} + \mathrm{CE} + \mathrm{BKE} + \mathrm{B\Phi E} + \mathrm{DE} \tag{2}$$

where DAE and DKE represent the local rates of change of eddy available potential energy (AE) and eddy kinetic energy (KE), respectively; CA, CK and CE are conversions; BAE, BKE and BΦE are boundary transports; and GE and DE represent generation and dissipation. A physical interpretation of the generation and conversion terms follows. GE increases AE when heating of warmer regions and cooling of colder regions at the same latitude occurs. CA acts to increase AE when horizontal and vertical transports of sensible heat by eddies are down their respective temperature gradients. CK, commonly referred to as the barotropic conversion term, increases KE when horizontal and vertical transports of absolute angular momentum by eddies are toward latitude bands and pressure levels of lower angular velocity. CE, referred to as a baroclinic conversion term, acts to increase KE when warmer air rises and colder air sinks within the same latitude belt.

All of the quantities in (1) and (2) were calculated from the aforementioned data except for the generation term, GE, and the sum, BΦE + DE, which were determined as residuals. The latter residual is designated

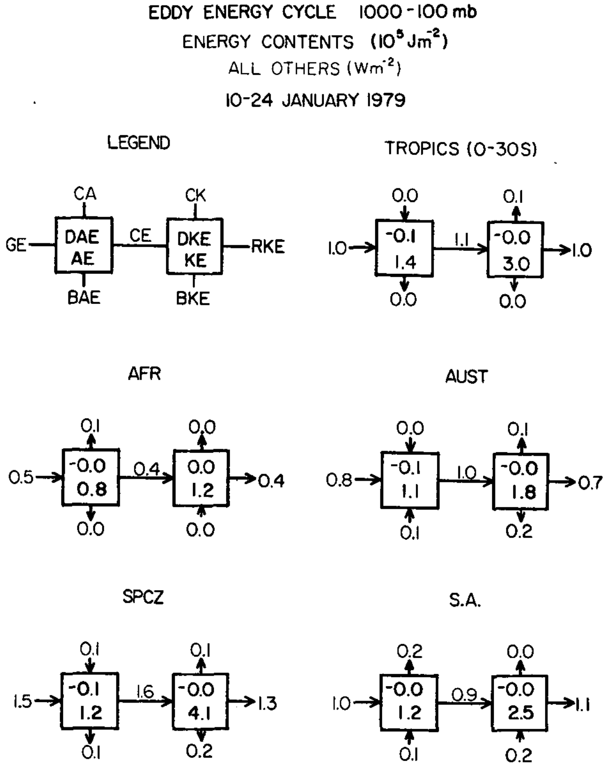

FIG. 2. Time-averaged eddy energy cycles for 0°–30°S and the four tropical regions defined in the text for the period 10–24 January 1979. Values are vertically-integrated and area-averaged, with contents in 10^5 J m^{-2} and other terms in W m^{-2}.

as RKE. A schematic diagram of the terms in (1) and (2) is shown in Fig. 2.

3. Results and discussion

a. *Eddy energy cycles*

The eddy energy cycles for the four equally-spaced tropical regions are presented in Fig. 2. For comparison, the eddy portion of the energy cycle for the total tropical Southern Hemisphere is also shown. It is seen that the main flow of energy in all four regions consists of a generation of AE, a conversion of AE to KE, and a loss of KE through the residual, RKE. The other conversion terms and the boundary fluxes of AE and KE are seen to be small. It is worth noting that no requirement exists for the value of any term averaged over the four regions to equal the hemispheric value, since latitude band averages were computed separately for each region.

In comparing the intensities of the eddy energy cycles among the four regions and the total tropics, Fig. 2 shows that the SPCZ region is the most active energetically. Although its AE content is comparable to that of the other regions, the KE content in the SPCZ region is the largest by far. This is because this region contains an upper-tropospheric subtropical jet. In the remaining three areas, the jet is confined to middle latitudes. According to Huang and Vincent (1983), the KE content in the SPCZ region remained at a high level for the period 10–24 January, after which it decreased rapidly. The decrease in KE corresponded well with the poleward shift of the subtropical jet out of the domain and with the observed weakening and decay of the SPCZ. The value of CE in the SPCZ region is about 1.5 times greater than that of the total tropics, suggesting that this region makes a significant contribution to the production of KE in the tropical Southern Hemisphere.

Figures 3 and 4 illustrate the vertically-integrated, area-averaged daily values of CE and CK. By comparison, the daily values of CA were near zero throughout the period; thus, its time series is not shown. For the total tropical Southern Hemisphere, Fig. 3 shows that CE peaks on 14 January and then decreases over most of the remaining period. At all times it is a source of KE, indicating a high correlation between warm air rising and cold air sinking in the tropics. In the African region, CE is small and oscillates about zero during the first 10 days of the period, after which it remains positive. As in the total tropics, CE is a source of KE throughout the 18 day interval for both the Australian and SPCZ regions. The largest CE values are seen to be in the SPCZ region where the trend is similar to that in the total tropics. Again, this demonstrates the important contribution that the SPCZ region makes

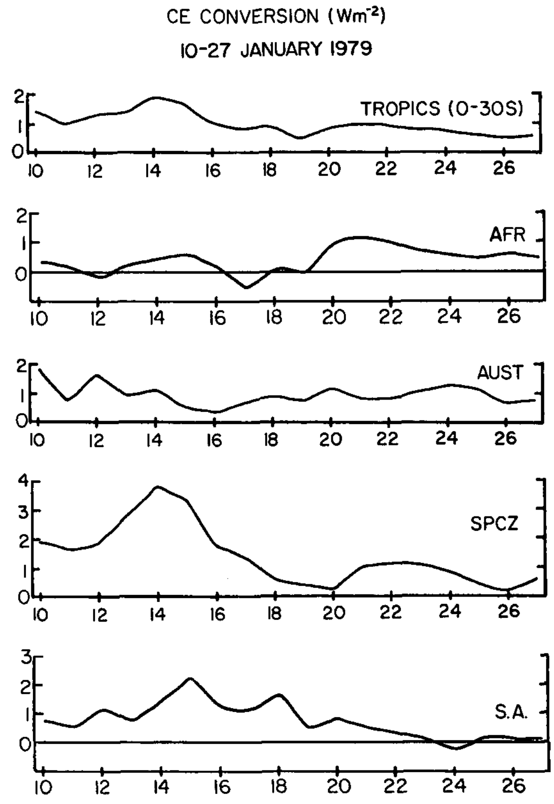

FIG. 3. Time series of vertically integrated area-averaged values at the CE conversion in W m^{-2} for 0°–30°S and the four tropical regions defined in the text during 10–27 January 1979.

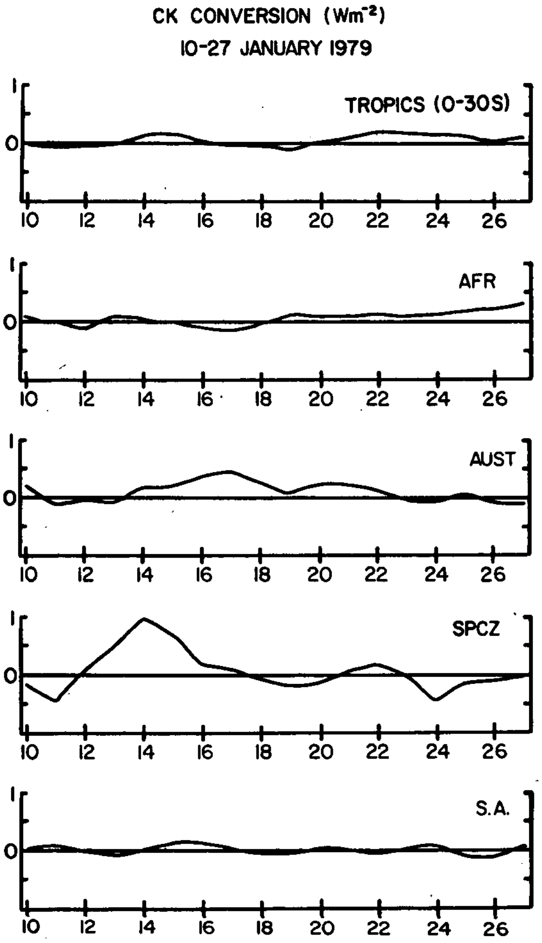

FIG. 4. As in Fig. 3 except for the CK-conversion in W m^{-2}.

to the tropical eddy kinetic energy budget. After reaching its maximum value on 14 January, CE in the SPCZ region decreases radiply to near zero by 18 January. Since it was noted above that the KE content of the region remains large and essentially constant from 14–18 January, the implication is that other energy budget terms are acting to maintain KE against the decrease due to CE. More is said later concerning this point. Finally, CE values in the South American region are positive on all days, except 24 January.

Except for the SPCZ region, Fig. 4 shows that values of CK are extremely small. In that region the main contribution of CE to the KE budget occurs over a few days near 14 January when it reaches a maximum value of 1 W m^{-2}. This shows that even though the residual, RKE, is the primary sink of KE in a time-averaged sense (see Fig. 2), CK does act as an important sink of KE (positive values indicate a destruction of KE) on certain days and helps to counteract the large source produced by CE. More importantly, as noted above, CE decreases substantially during the period 14–18 January; therefore, another term (or terms) in the KE budget must be acting to maintain the observed constant high level of KE. Comparing Figs. 3 and 4, it is seen that the trends (decreasing values) of CE and CK are similar from 14–18 January. Consequently, although the magnitudes of the terms are not the same, the similarity in their trends provides evidence that CK is partially responsible for maintaining KE against the decrease occurring in CE.

b. Relationship between the SPCZ and South American regions

One of the more intriguing aspects of the study is the relationship between the SPCZ and South American regions. Recent studies by Kalney and Halem (1981), Kalnay and Paegle (1983), and HV have verified that both the SPCZ and SACZ were quasi-stationary persistent features of the large-scale circulation pattern throughout most of January 1979. However, Kalnay and Halem (1981) noted that both features either disappear or weaken considerably in the second half of SOP-1, beginning 4 February. Recently, Kalnay et al. (1986) performed two 15-day control forecast experiments using the Goddard Laboratory for Atmospheres (GLA) Fourth-Order General Circulation Model (GCM) and initial conditions corresponding to 5 January and 4 February 1979 to forecast the existence of these wave features in January and their absence in February. The success of the model provided a powerful tool to determine the origin of the waves through a series of mechanistic experiments.

Of greatest interest to the present study was their third experiment in which they attempted to determine whether or not convection in the central Pacific was important in maintaining the South American waves. They approached this by reducing the latent heat of condensation to one tenth of its value over a 180° longitude sector, centered on the dateline for all latitudes. The result was not only a large reduction in amplitude of the South American waves, but also an eastward propagation of the previously stationary feature. From

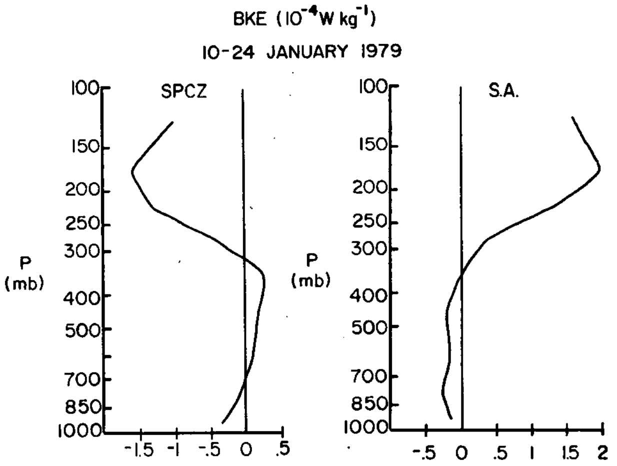

FIG. 5. Vertical distributions of the time and area-averaged eddy kinetic energy boundary transport, BKE, in 10^{-4} W kg^{-1} for the SPCZ and South American (S.A.) regions for 10–24 January 1979.

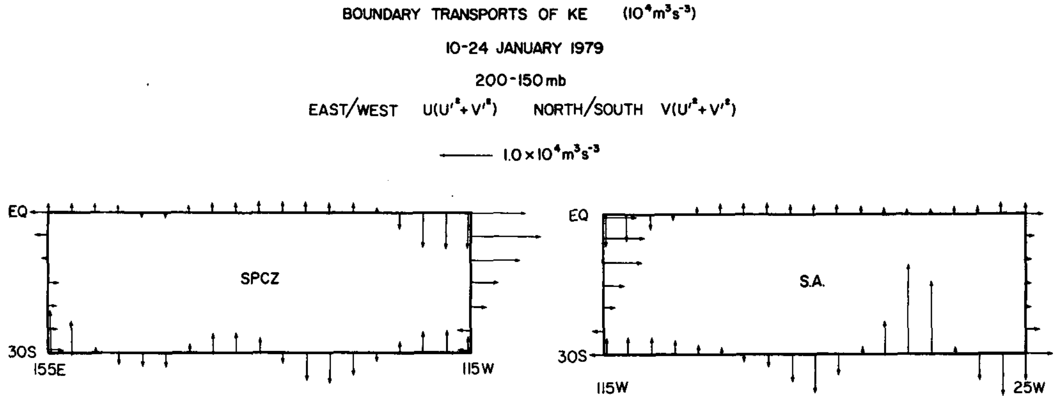

FIG. 6. Time-averaged fluxes of eddy kinetic energy in 10^4 m^3 s^{-3} in the 200–150 mb layer across the borders of the SPCZ and South American (S.A.) regions for 10–24 January 1979.

this, they concluded that subtropical convection in the SPCZ region plays an important role in the maintenance of the South American waves, and they attributed the eastward propagation to a change in the Walker circulation associated with the SPCZ.

The primary tool that can be used to examine the relationship between the SPCZ and South American regions in the present study is an evaluation of the boundary flux (BKE) of eddy kinetic energy across the common border of the regions. Vertical distributions of the area-averaged values of BKE for each region are illustrated in Fig. 5 and show that the profiles are virtually mirror images of each other. Most importantly, large losses (gains) of KE are observed in the upper troposphere of the SPCZ (South American) region where the zonal component of the wind is the greatest. These results hint at the possibility that some of the eddy kinetic energy from the SPCZ is helping to maintain the KE content in the South American region, with the primary transport taking place in the upper troposphere.

The time-averaged fluxes of eddy kinetic energy across the borders of the SPCZ and South American regions are illustrated in Fig. 6 for the 200–150 mb layer. This layer is examined because it contained the largest fluxes of eddy kinetic energy. The salient feature is the large flux of KE from the SPCZ region into the South American region across 115 W. This transport is seen to be very significant, especially at low latitudes. Furthermore, this result seems to be in good agreement with the conclusions drawn by Kalnay et al. (1986), namely that a Walker-type of circulation associated with the SPCZ is a contributor to the maintenance of the SACZ. At lower levels in the troposphere (not shown), transports between the two regions are much smaller and more variable.

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