On the Maintenance of Short-Term Subtropical Wind Maxima in the Southern Hemisphere during SOP-1, FGGE

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ABSTRACT

The extent to which divergent circulations, induced by tropical heating, help to maintain westerly maxima in the Southern Hemisphere subtropics during the SOP-1 of FGGE is explored using Level III-b analyses from the Goddard Laboratory for Atmospheres (GLA). The contribution of the divergent wind component to the total ageostrophic flow in the subtropics is examined, as are the roles of other forcing terms in the localized Eliassen–Palm flux zonal momentum equation. In addition, the interaction of divergent and rotational flows in the subtropics is analyzed using the complete kinetic energy budget, partitioned into rotational and divergent components.

Throughout the summertime subtropics, it is generally found that the dominant term in the zonal momentum budget is the Coriolis force applied to the diabatically driven meridional circulation. The largest positive tendencies due to this term are found in the entrance regions of the subtropical westerly maxima, and divergent circulations account for nearly all of the total ageostrophic flow. In the SPCZ region, however, it is found that transient eddies play an important role by partially offsetting the strong Coriolis acceleration in the entrance region of the local jet, and they help accelerate the westerly flow in the exit region through both barotropic and baroclinic processes. Energetically, the dominant term in the rotational kinetic energy budget throughout the subtropical belt is the conversion of divergent to rotational kinetic energy. Furthermore, nearly all of the generated divergent kinetic energy is converted. The evidence from all of these approaches supports the view that tropical heating in transient events drives or enhances local meridional overturning in the atmosphere, which, in turn, strengthens the summer subtropical westerly jet stream.

1. Introduction

In a recent paper, Hurrell and Vincent (1990, hereafter referred to as HV) examined the relationship between upper tropospheric outflow from tropical heat sources and subtropical wind maxima in the Southern Hemisphere during the SOP-1, FGGE. Using NASA GLA Level III-b analyses, a good correlation was found between episodes of maximum tropical heating (as inferred from the velocity potential) and the strengthening and propagation of westerly wind maxima in the subtropics. This relationship was most evident over the central South Pacific and western Indian oceans. The purposes of the present study are: 1) to extend our previous analyses by quantitatively examining the extent to which the diabatically driven divergent circulations interact with, and accelerate, the subtropical westerlies and 2) to supplement our earlier results by examining the roles of other local forcings on the observed wind maxima. Several new analysis tools will be utilized. These include a partitioning of the ageostrophic wind into divergent and rotational components (Trenberth and Chen 1988), applications of localized Eliassen–Palm (E–P) flux diagnostics (Trenberth 1986), and an examination of the complete kinetic energy budget, separated into rotational and divergent components (Chen et al. 1988).

The present study focuses on an aspect of the circulation not well examined before; namely, interactions within the summer hemisphere that occur over relatively short time scales are investigated. Nearly all previous studies have used seasonal data to examine the impact of tropical heating on subtropical rotational flows in the winter hemisphere (e.g., Lau 1978; Krishnamurti 1979; Physik 1981; Paegle et al. 1983; Chen et al. 1988). As shown in HV, however, important deviations can occur in tropical heating on monthly and shorter time scales and, at least for the SOP-1,

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these deviations appear to be most closely tied to redistributions of the summer hemisphere subtropical zonal winds. For this reason, the more subtle forcing of the weaker summertime wind maxima is an equally important subject that needs to be addressed. Also, wind maxima over oceanic regions is emphasized, in contrast to the aforementioned studies. As Paegle et al. (1983) point out, the forcing of wintertime jet cores located over or near the coastlines of continents is additionally complicated by the fact that the jets may be primarily driven by the baroclinic instability established by the strong thermal contrasts of land and ocean. Only the more recent studies of tropical intraseasonal oscillations have examined the variability of westerly maxima over the oceans. However, the relationships between tropical heating anomalies and subtropical westerly accelerations have not been emphasized in these investigations and often are not considered.

The results presented in HV primarily emphasized the daily variability of the Southern Hemisphere tropical heating and subtropical zonal winds during the entire SOP-1. In addition, we also examined the mean state of two 15-day periods, 6–20 January (period 1) and 3–17 February 1979 (period 2), that captured major changes in both variables. In general, convection in the South Pacific convergence zone (SPCZ) was very strong during the January period, while convective activity increased substantially from the end of January until the middle of February over the Indian Ocean. In each region, the corresponding enhancements of divergent outflow were highly correlated to increases in the subtropical westerlies located about 15° latitude south of the maximum heating. Since the out-of-phase relationship between the Pacific and Indian ocean regions was addressed in HV, most of the discussion in this article will be limited to results from period 1. This allows us to focus on tropical–subtropical interactions within the SPCZ, one of the most extensive and persistent features of the general circulation.

2. Data and analysis techniques

a. Data sources

This study uses the special dataset produced by NASA from the First Special Observing Period of the Global Weather Experiment, the GLA FGGE SOP-1 Level III-b analyses, described in detail by HV. Only a brief summary is given here. The dataset contains objectively analyzed values of horizontal wind components (u, v) and geopotential height (z) and derived values of temperature (T) and vertical p velocities (ω) at grid increments of 4° latitude by 5° longitude. All variables were interpolated from sigma to pressure coordinates and were available at 12 mandatory levels; however, only the upper-tropospheric values (i.e., 250, 200, 150 mb) are used in the present study. Temporally, all calculations were made with 0000 and 1200 UTC analyses.

b. Rotational and divergent wind components

As noted by Nogues-Paegle and Mo (1987) and Nogues-Paegle and Zhen (1987), any study that attempts to explain possible relationships between low-latitude heating and subtropical westerly maxima in terms of local Hadley-type circulations must be able to reliably determine the divergent wind components. It appears that the GLA analyses provide sufficient accuracy for this purpose, especially when compared to other available FGGE datasets (e.g., Paegle et al. 1983, 1985). For two-dimensional flow, Helmholtz's theorem states that

$$\mathbf{v} = \mathbf{v}_\psi + \mathbf{v}_\chi \tag{1}$$

where

$$\mathbf{v}_\psi = \mathbf{k} \times \nabla_\psi, \quad \mathbf{v}_\chi = \nabla\chi \tag{2}$$

where ψ is the streamfunction for the rotational part of the wind and χ is the velocity potential for the divergent component (a complete derivation of velocity potential and streamfunction is given by Hendon 1986). The vorticity and divergence now become

$$\zeta = \mathbf{k}\cdot\nabla\times\mathbf{v} = \nabla^2\psi, \quad \delta = \nabla\cdot\mathbf{v} = \nabla^2\chi. \tag{3}$$

These Poisson equations were solved for ψ and χ using the overrelaxation method (Haltiner and Williams 1980) over the entire globe, so as to eliminate the need for boundary conditions. An overrelaxation factor of 1.6 was found to give the maximum rate of convergence, and a first guess of zero was applied in both cases. Calculations were continued until the largest relative error between successive iterations was less than one percent.

It is of interest in this study to determine the contribution of the divergent wind to the total ageostrophic wind and, thus, to the tendencies due to the Coriolis force in the momentum equation. To investigate this, a new technique described by Trenberth and Chen (1988) was utilized in the present study. Briefly, they noted that it has been traditional in meteorology to separate the velocity field into rotational and divergent components as described above. Since it is not possible to uniquely partition a scalar quantity, the same has never been done to the geopotential field. Such a partitioning can be made, however, whenever a balance relation is defined. In particular, Trenberth and Chen derived a unique form of the linear balance equation (LBE) that separates the total geopotential into rotational (Φ_ψ) and divergent (Φ_χ) components [their Eqs. (8) and (9)]. From this partitioning, the Coriolis and geopotential terms that make up the geostrophic relation in the u-momentum equation corresponding to the LBE can be written as

$$fv_a = \left(fv_\psi - \frac{\partial\Phi_\psi}{\partial x}\right) + \left(fv_\chi - \frac{\partial\Phi_\chi}{\partial x}\right) \tag{4}$$

or

$$fv_a = \frac{\partial \gamma}{\partial y} + \left(fv_\chi - \frac{\partial \Phi_\chi}{\partial x} \right) \tag{5}$$

where v_a is the meridional ageostrophic velocity and $\gamma = \nabla^{-2}(\beta v_\psi)$, following the notation of Trenberth and Chen. The first two terms in (4) have been combined to form the first term in (5) from a relationship that arises through the integration of the LBE. This term is associated with the divergence of the geostrophic wind arising from the variable Coriolis parameter. The important point is that (5) represents a new interpretation of the total ageostrophic meridional wind, which is seen to consist of a rotational part (the γ term) and a divergent part. Moreover, the divergent component is not restricted to fv_χ.

In order to quantitatively relate tropical heating to subtropical jet accelerations, it is also necessary to compute the component of the tropical divergent wind that is driven by the diabatic heating. To accomplish this goal, the approach of Chen and Yen (1991) was followed. Begin with the thermodynamic equation in the form

$$\frac{1}{\sigma c_p} \dot{Q} = \frac{1}{\sigma} \left(\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) - \omega \tag{6}$$

where σ is the static stability parameter defined in the usual way:

$$\sigma = \frac{RT}{c_p p} - \frac{\partial T}{\partial p}.$$

Differentiating (6) with respect to pressure, rearranging terms, and substituting from the isobaric continuity equation yields

$$\chi = \nabla^{-2} \left\{ \frac{\partial}{\partial p} \left[\frac{1}{\sigma c_p} \dot{Q} \right] \right\} - \nabla^{-2} \left\{ \frac{\partial}{\partial p} \left[\frac{1}{\sigma} \left(\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) \right] \right\} \tag{7}$$

or

$$\chi = \chi_Q + \chi_T.$$

Equation (7) allows for the diabatically driven velocity potential (χ_Q) to be obtained as a residual, and from (2) the diabatic component of the divergent wind can be obtained from $\nabla \chi_Q$. This result will be compared to the "residual" circulation, also driven diabatically, which is obtained from the localized Eliassen–Palm flux calculations. It will be shown that both estimates are not only in good agreement with each other but, more importantly, that both account for nearly all of the total divergent wind in the tropics. It is worth noting that we made no attempt in this study to obtain an independent estimate of the vertical profile of diabatic heating so that the residual term in (7) could be computed directly. Thus, our interpretation of χ_Q as being diabatically driven should be viewed as a reasonable assumption, and the uncertainties inherent to any residual term should be kept in mind.

c. *Localized Eliassen–Palm flux diagnostics*

In addition to examining the ability of tropical heating to accelerate subtropical westerly wind maxima through the Coriolis force applied to poleward-moving divergent outflow, it would be remiss not to consider other processes that could possibly affect the zonal wind. Traditionally, the maintenance of the zonal wind has been examined with the use of the Eulerian zonal momentum equation (e.g., Newell et al. 1974; Physick 1981; Trenberth 1987). From this equation, it is well known that the upper tropospheric westerlies are largely maintained by the convergence of westerly momentum by the large-scale eddies. On the other hand, an analysis of the temperature tendency equation reveals that these same eddies are responsible for a large poleward heat flux that acts to reduce the equator-to-pole temperature gradient and, thus, the thermal wind. From this point of view, it seems as though the eddies must be acting to reduce the strength of the westerlies. More recently, increasing attention has been given to a new diagnostic, the Eliassen–Palm (E–P) flux, **F** (Eliassen and Palm 1961; Andrews and McIntyre 1976; Hoskins et al. 1983; Plumb 1985, 1986; Trenberth 1986, 1987; Pfeffer and Lu 1989), which allows for a determination of the net effect of the large-scale eddies on the zonal flow.

In order to determine the net effect of the eddies in maintaining the westerlies, it is necessary that the momentum and thermodynamic equations be transformed in such a way that the eddy fluxes of heat and momentum are combined into one term that is unique to the transformed momentum equation. This single term is the divergence of **F** (i.e., $\nabla \cdot \mathbf{F}$). For the zonal mean equations, the transformation is developed and described in detail by Andrews and McIntyre (1976). In their development, **F** is a vector in the meridional plane whose upward and equatorward components are proportional to the poleward eddy flux of heat and angular momentum, respectively. Since it is not the purpose of the present study to examine the maintenance of the zonal mean westerlies, a more appropriate form of **F** that allows for the determination of the net impact of transient eddies on the local time-mean flow is utilized. This "localized" Eliassen–Palm flux was developed by Trenberth (1986), and the reader is referred to his work for a complete derivation of the transformed equations. Trenberth examined the impact of transient eddies on the zonal flow during a Southern Hemisphere midlatitude blocking episode, and the results presented were based on a simplified quasi-geostrophic form of the complete equations. The transformed equations presented below do not include the quasi-geostrophic simplifications and are derived from the primitive mo-

mentum, thermodynamic, and continuity equations in spherical geometry. They are similar to those presented in his appendix A, with the primary difference being that they are written in a pressure coordinate system [Trenberth used a vertical coordinate of $z = \ln(p_0/p)$, where p is pressure and $p_0 = 1000$ mb]. Since his notation is being retained, it is important to note that the localized E–P flux is denoted by the symbol $\mathbf{E}_u$, rather than $\mathbf{F}$. Also, only the transformed zonal momentum equation is presented.

In spherical geometry, the transformed time–mean zonal momentum equation is

$$\underset{(A)}{D_3\bar{u}} - \underset{(B)}{\frac{\overline{uv}\tan\phi}{a}} - \underset{(C)}{fv^*} - \underset{(D)}{\frac{\partial\gamma}{a\partial\phi}} = \underset{(E)}{\frac{1}{\cos\phi}\nabla\cdot\mathbf{E}_u} + \underset{(F)}{F_x}, \tag{8}$$

where

$$\mathbf{E}_u = \left[\frac{1}{2}(\overline{v'^2} - \overline{u'^2}), -\overline{u'v'}, -\left(\frac{f}{\sigma}\overline{v'T'} + \overline{u'\omega'}\right)\right]\cos\phi \tag{9}$$

$$\gamma = \nabla^{-2}(\beta\bar{v}_\psi)$$

$$v^* = \bar{v}_x + \frac{\partial}{\partial p}\frac{\overline{v'T'}}{\sigma} \tag{10}$$

and the divergence operator in (8) is given by

$$\nabla = \left[\frac{1}{a\cos\phi}\frac{\partial}{\partial\lambda}, \frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\cos\phi, \frac{\partial}{\partial p}\right].$$

In the above equations, overbars denote a time average over a 15-day period and primes denote a deviation from the time average. All other symbols have their usual meteorological meanings. Term D in (8) arises from the integration of a balance equation that is an extension of the LBE [see Eq. (A7), Trenberth]. It is related to the divergence of the geostrophic wind from the variable Coriolis parameter and is similar to the γ term in (5). Otherwise, the terms in (8) are (A) the three-dimensional mean advection, (B) the curvature term, (C) the Coriolis force, (E) the divergence of $\mathbf{E}_u$, and (F) friction. All terms were computed except for friction, which was solved for as a residual. In general, the Coriolis term and the $\mathbf{E}_u$ divergence were found to be the largest and often accounted for the primary momentum balance in the subtropics. In some subtropical regions, however, the mean advection and the γ term also made significant contributions. The $\mathbf{E}_u$ vector, defined by (9), is seen to consist of horizontal eddy momentum flux (barotropic) and vertical eddy heat and momentum flux (baroclinic) components. Note that in the zonal mean, the barotropic component reduces to the horizontal eddy flux convergence term found in the standard zonal momentum equation.

The Coriolis term in (8) deserves special attention in the present investigation because of the unique interpretation of v^*, defined by (10). As discussed by Trenberth and others, v^* is the meridional component of the "residual" mean circulation (u^*, v^*, ω^*). The term "residual" simply refers to that part of the mean circulation that resides after the convergence of eddy heat transport is removed from the Eulerian equations. Thus, v^* can be interpreted as the diabatically driven divergent meridional wind and can be compared to the meridional component of $\nabla\chi_Q$ obtained from (7). Again, this represents a quantitative approach to examine the impact of the meridional circulation induced by tropical heating on the westerly wind field. No prior studies have adopted this approach.

While attention in this study will be focused on (8) to determine the diabatically driven Coriolis force and the E–P flux divergence as a measure of the net eddy forcing of the time–mean zonal flow, it is necessary to realize, however, that an eddy forcing term ($\nabla\cdot\mathbf{E}_v$) also appears in the transformed meridional momentum equation and can impact the zonal flow by driving the meridional circulation. For time-mean flows in the Southern Hemisphere, however, the latter was found to be very small. In addition, the interpretation of the "residual" circulation as being forced solely by the diabatic heating field, independent of the effect of the eddies, is clearly not correct. In reality, the eddies are interactive with the diabatic heating field and it is impossible to totally isolate these processes in either (7) or (8).

d. Budgets of rotational and divergent kinetic energy

As a result of partitioning the wind field into rotational and divergent components, it follows that another useful diagnostic tool to investigate the interaction between these components is the budgets of rotational and divergent kinetic energy. As discussed previously, it will be shown that, in the Southern Hemisphere tropics during the SOP-1, the diabatically driven divergent flow nearly accounts for the total divergent velocity. Likewise, the rotational flow essentially depicts the subtropical westerly wind maxima. Therefore, the conversion term that links the rotational and divergent kinetic energy budgets can give meaningful insight into the extent to which the divergent flow generated by the tropical heating is supporting the subtropical westerlies (or vice versa).

The budgets of rotational and divergent kinetic energy were originally formulated for a closed domain by Chen and Wiin-Nielsen (1976) and for an open domain by Chen et al. (1978). Chen et al. (1988) used the open domain equations to examine the maintenance of the winter subtropical jet streams in the Northern Hemisphere. Hurrell and Vincent (1990) used an approximate form of these equations to examine the conversion term in the Southern Hemisphere

subtropics during the entire SOP-1. It is relevant to the goals of the present study, however, to expand our previous work and examine the complete energy budget so as to determine all processes contributing to the maintenance of the time-mean rotational winds.

The complete energy budget is shown in symbolic form in Fig. 6. Since it is only applied at the subtropical westerly maximum level (i.e., 200 mb), the energy equations are not vertically integrated to yield the total kinetic energy. The derivation of these equations, as well as an excellent discussion of the physical interpretation of the various terms, is given by Buechler and Fuelberg (1986). Briefly, the generation terms $G(k_\psi)$ and $G(k_\chi)$ are positive for downgradient cross-contour flow. The horizontal flux divergence of total kinetic energy (k) by $\mathbf{v}_\psi$ and $\mathbf{v}_\chi$ is denoted by the terms HFR(k) and HFD(k). The vertical flux divergence, present only in the k_χ budget, is given by VFD(k). The conversion term is denoted by $C(k_\chi, k_\psi)$ and is positive for the conversion of divergent to rotational kinetic energy. The terms INTR and INTD arise from the dot product of $\mathbf{v}_\psi$ and $\mathbf{v}_\chi$ in the total kinetic energy equation and are interaction terms between k_ψ and k_χ due to the presence of the other component. In this study, and others, both of these terms are very small. Finally, R_ψ and R_χ were computed as residuals and, therefore, contain the combined effects of dissipation due to frictional effects, transfers of energy between the grid scale and subgrid scale, and the accumulation of errors from other terms.

3. Results and discussion

a. Divergent circulations

As discussed in HV, the strongest tropical convection during period 1 (6–20 January 1979) was observed in the Southern Hemisphere and extended from Indonesia across the international date line (IDL) into the SPCZ. Strong convection was also noted over Africa and South America. Evidence of this activity is given in Fig. 1, which presents a vector plot of the total divergent wind at 200 mb overlayed on a contour plot of the zonal wind component. For reference, note that the maximum divergent wind speed (indicated by the length of the maximum vector) is 8.0 m s^{-1}. It is clear that the strongest outflow in the Southern Hemisphere tropics during period 1 is from the Indonesian and SPCZ regions. In agreement with most prior studies, much of this outflow is directed across the equator into the Northern Hemisphere and converges into the east Asian jet region. Of most relevance to the present study, however, is the strong meridional outflow directed toward the Southern Hemisphere subtropics and, in particular, toward the vicinity of a local maximum of westerly flow near 26°S and just east of the IDL. This maximum, which is in excess of 30 m s^{-1}, is strongest in the subtropics. Moreover, it is distinctly separate from the higher-latitude jet stream near 50°S. The magnitude of the meridional divergent flow is a maximum in the entrance region of this westerly jet and is less than −4 m s^{-1}. Apparently, this represents a significant Coriolis acceleration of the zonal wind.

In other regions, there is a subtropical westerly maximum oriented from southwest to northeast across South America and a band of strong westerlies near the equator over the eastern Pacific Ocean. The former is also located in a smaller region of poleward-moving divergent outflow less than −2 m s^{-1} associated with the South Atlantic convergence zone (SACZ). As discussed by HV, changes in the subtropical westerlies over South America during the SOP-1 also appear to be well correlated to changes in the convective activity within the SACZ, but the relationship is not as well defined as over the western Pacific and Indian oceans.

The tropical westerly maximum over the eastern Pacific is a particularly interesting feature. The existence of a westerly flow region of limited zonal extent over the Southern Hemisphere eastern tropical Pacific Ocean at 200 mb has also been noted in the seasonal data of Newell et al. (1972) and Sadler (1975). Webster

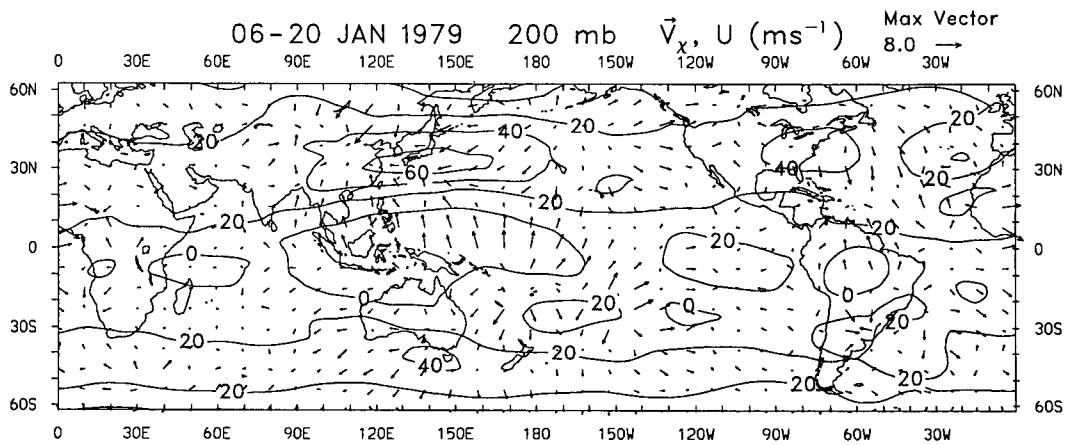

FIG. 1. Vector plot of the divergent wind and contoured plot of the zonal wind component at 200 mb in m s^{-1}.

and Holton (1982), using a shallow-water model, have pointed to the existence of this westerly "duct" as representing a corridor for cross-equatorial interactions. During the SOP-1, the relationship of this tropical maximum to convective activity is not clear. From late January through mid-February, when the convective activity in the SPCZ weakened considerably and the strongest convection shifted to the west of the IDL and over the Indian Ocean, the eastern Pacific jet weakened by more than 10 m s^{-1} and also shifted westward. No significant change, however, was noted in the analyzed divergent wind over the tropical eastern Pacific. Hurrell and Vincent (1992), in a series of 17-day integrations performed with a recent version of the GLA fourth-order GCM, reduced the latent energy supplied to the atmosphere over the SPCZ region in January 1979 and found a decrease in the magnitude of the eastern Pacific jet similar to the observed decrease. Moreover, this change appeared to be related to a strong reduction of the Walker circulation over the tropical central and eastern Pacific in the model atmosphere. Perhaps the lack of a significant change in the observed divergent velocities over the eastern Pacific between January and February 1979 indicates a shortcoming in the FGGE analyses over this particularly data-void region.

Another interesting and important point relevant to Fig. 1 is that the divergent wind appears to play a much more important role in forcing the summertime subtropical westerly maxima than in forcing the climatological Northern Hemisphere wintertime jet cores. In general, the strongest poleward-moving divergent flow in the Northern Hemisphere is located south of 20°N, approximately 10° south of the main jet streams and at latitudes where the Coriolis parameter is small. In the Southern Hemisphere, however, Fig. 1 shows that the maximum values of v_x are located at the latitudes of the SPCZ and SACZ westerly maxima. The same is true during period 2 (not shown) when the strongest outflow was located near the entrance regions of maximum westerlies over the Indian Ocean and between Australia and New Zealand.

To further investigate the contribution of v_x to the total meridional ageostrophic wind (v_a) in the subtropics, all terms in (5) were computed. The differences between the summer and winter circulations are clearly illustrated in Fig. 2, which shows fv_a and fv_x for period 1. There are strong accelerations by fv_a in the jet entrance regions over east Asia and North America, with values over 40 m s^{-1} day^{-1}. The exit regions over the Pacific and Atlantic are marked by strong decelerations in excess of 30 m s^{-1} day^{-1} and 50 m s^{-1} day^{-1}, respectively. Figure 2b shows that fv_x accounts for no more than approximately one-third of these acceleration patterns. As found by Trenberth and Chen (1988), the primary components of the meridional ageostrophic flow in the winter jet stream regions were largely rotational and arose through kinematic requirements. Specifically, the rotational term in (5) (not shown) accounted for more than half of the total acceleration.

In contrast, in the Southern Hemisphere subtropics, fv_x was found to account for much of the Coriolis acceleration. Figure 2a shows that fv_a causes an acceleration of 31 m s^{-1} day^{-1} at the entrance region of the SPCZ westerly maximum; moreover, fv_x accounts for about 90 percent of this acceleration (28 m s^{-1} day^{-1} at the same grid point). The same was found to be true over the western Indian Ocean during period 2 (not shown), where fv_x accounted for nearly all of the westerly acceleration caused by fv_a (slightly more than 20 m s^{-1} day^{-1}). What is important to keep in mind is that these results were not totally anticipated, especially for the SPCZ jet. During period 1 in the central Pacific, the SPCZ was associated with a very pronounced trough/ridge system (Vincent 1982; Huang and Vincent 1985). Later, it will be shown that supergeostrophic rotational flow through this trough/ridge system results in the negative generation of rotational kinetic energy. Consequently, it might have been expected that the rotational term in (5) would have made a significant contribution to v_a in this region. Although the rotational term was found to be positive in the entrance region, it was only 2 m s^{-1} day^{-1}. This leads us to conclude that the meridional divergent wind does account for the major portion of the total meridional ageostrophic circulation in the entrance regions of the Southern Hemisphere subtropical westerly maxima during the SOP-1. We now examine the extent to which this component is tied to changes in convective heating.

To quantitatively relate changes in the 200-mb meridional divergent wind to changes in tropical convection, the diabatically forced component of $v_x(v_{xQ})$ was computed for periods 1 and 2. The results for period 1 are shown in Fig. 3 for the SPCZ region only. It is seen that v_{xQ} accounts for nearly all of v_x, especially in the entrance region of the SPCZ westerly maximum. The same result was found in the western Indian Ocean during period 2. It is especially interesting to compare this result to the meridional component of the "residual" circulation (v^*) shown in Fig. 3c. This variable was obtained from (10) and is an important component of the localized Eliassen–Palm flux calculations, which will be presented momentarily. In general, there is a very close agreement between v^* and v_{xQ}. Thus, it appears reasonable to assume that nearly all of the divergent flow in the regions of the subtropical Southern Hemisphere westerly maxima is directly forced by the tropical convection.

b. *Localized E–P flux diagnostics*

The results presented thus far have illustrated the importance of the Coriolis term in the traditional zonal momentum equation to the forcing of the summertime

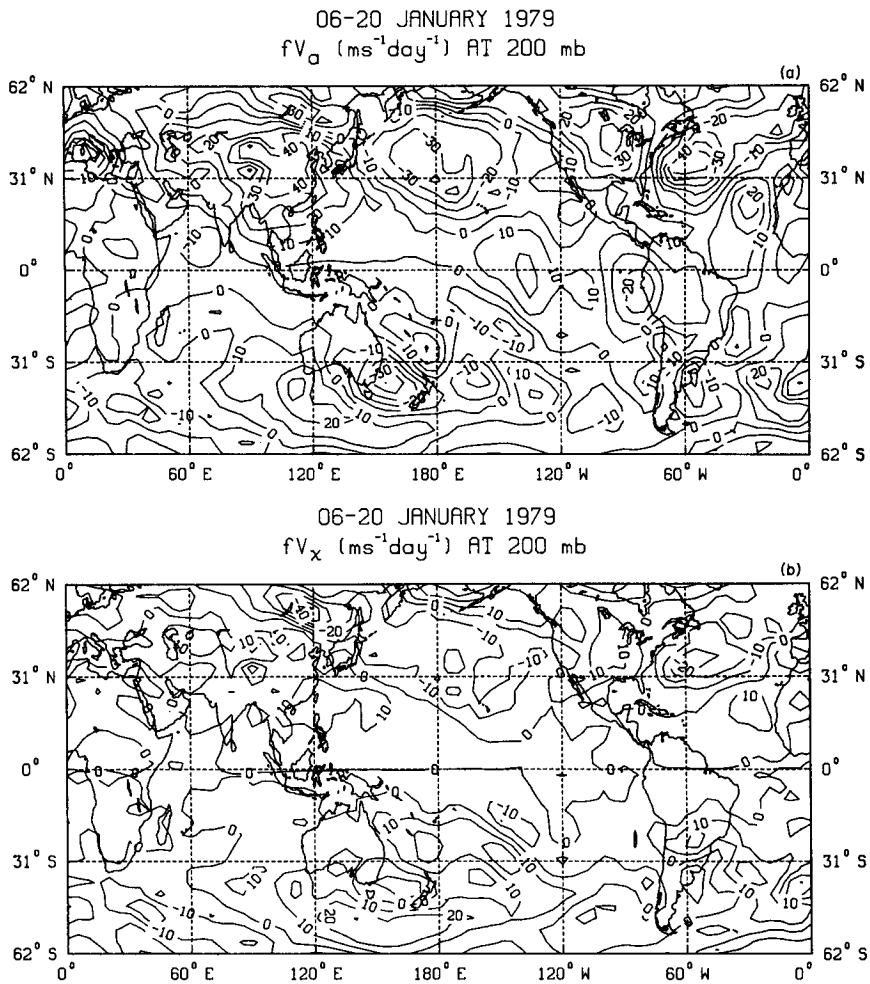

FIG. 2. (a) Coriolis force due to the ageostrophic meridional wind component at 200 mb in m s^{-1} day^{-1} and (b) the same due to the meridional component of the divergent wind.

subtropical westerly maxima during the SOP-1. Moreover, it has been demonstrated that the diabatically driven meridional divergent wind is the dominant component of this term. On the other hand, other terms present in the zonal momentum equation can also act to accelerate the wind field, and it is important to consider these processes as well. As discussed in section 2, the diagnostic tool used to investigate the balance of the time-mean zonal momentum equation is the localized E–P flux equations derived by Trenberth (1986). The terms in (8) were computed globally for both period 1 and period 2, although the main interest was in the Southern Hemisphere subtropics. In particular, over the Indian Ocean during period 2, it was found that the dominant term in the transformed momentum equation was the Coriolis force (fv^*) applied to the diabatically forced meridional divergent flow. All other terms in this region were small, including the E–P flux divergence. The latter result is in good agreement with other analyses (e.g., daily plots of sea level pressure) that indicate a lack of cyclone activity over this region during February. Over the South Pacific region, however, it is well documented that the SPCZ is a genesis region for tropical cyclones (Streten and Troup 1973; Trenberth 1976). Furthermore, as discussed by Vincent (1985) and Robertson et al. (1989), at least three cyclones propagated along the cloud band from 10–18 January 1979, and it seems logical to expect that they might have played an important role in the maintenance of the subtropical westerly maximum through the convergence of eddy momentum and heat fluxes. Consequently, the remaining discussion in this section will focus on the South Pacific during period 1.

With the exception of Trenberth (1986) and the related formulations of Hoskins et al. (1983) and Plumb (1985, 1986), most previous studies that have utilized the E–P flux diagnostic to determine the net effect of

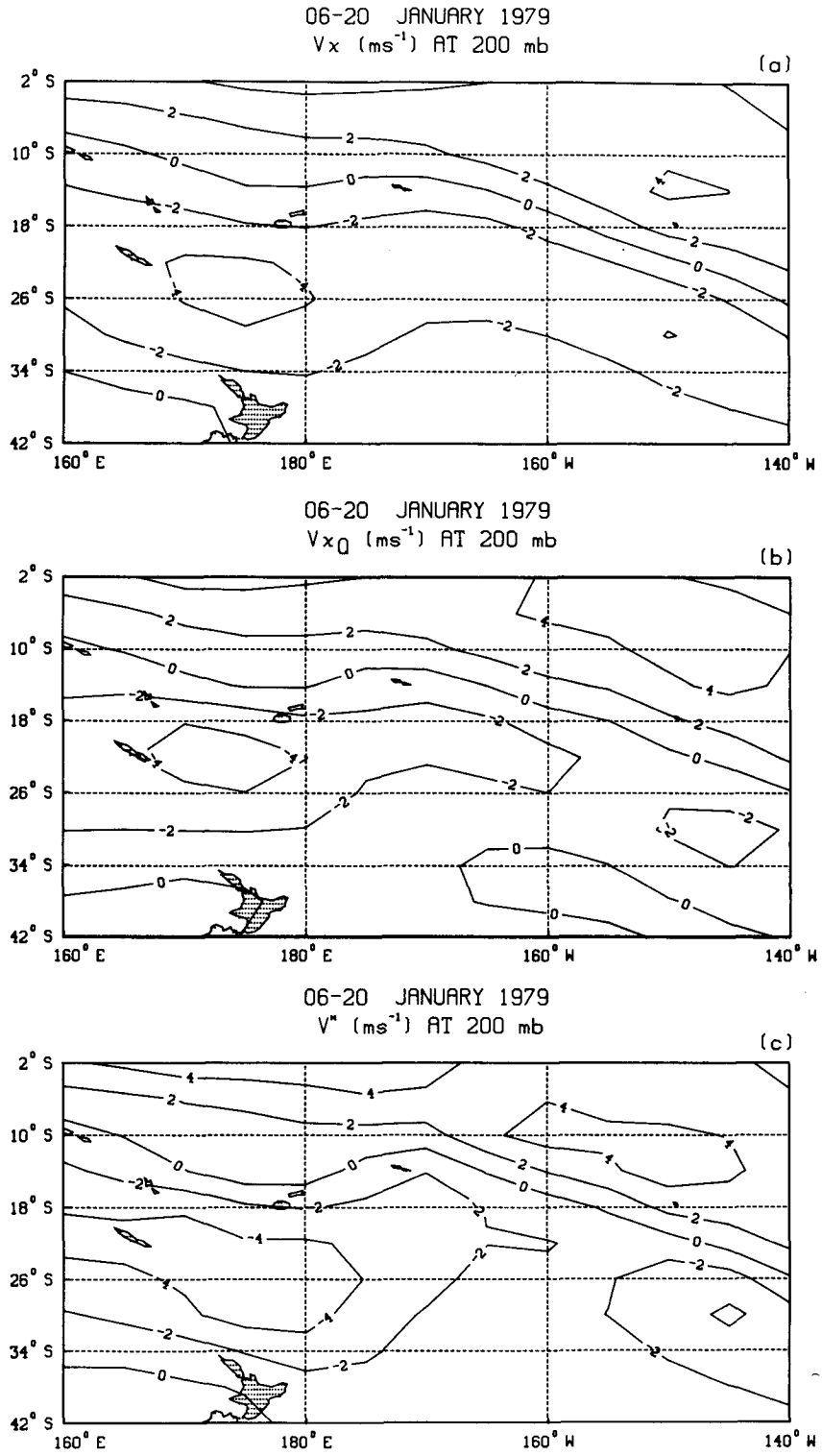

FIG. 3. Meridional components of the wind at 200 mb in m s^{-1} for (a) the total divergent flow, (b) the diabatically driven divergent flow, and (c) the "residual" flow. See text for details.

large-scale eddies on the zonal flow have used a zonal mean form of the transformed momentum equation. In the zonal mean case the E–P flux can be written in terms of transient and stationary eddy components, and the relative role of each component in supporting the westerly flow can be determined. Figure 4 illustrates a zonal average, taken over a 40-degree longitude band covering the extent of the South Pacific westerly maximum (Fig. 1), of the 200-mb u wind over the latitudes of the Southern Hemisphere tropics and midlatitudes during period 1. The SPCZ jet is clearly shown in Fig. 4 as a relative maximum of 26 m s^{-1} at 26°S. As discussed earlier, this maximum is distinct from the higher-latitude westerlies near 50°S and is of comparable magnitude. Also shown in Fig. 4 is the total E–P flux divergence, as well as the transient and stationary eddy components of the divergence. In general, it is seen that, outside the deep tropics, E–P flux divergence (convergence) occurs at latitudes where the westerlies are a maximum (minimum). In particular, eddy processes are acting to accelerate the westerlies approximately 4.7 m s^{-1} day^{-1} at 26°S and 3.8 m s^{-1} day^{-1} at 50°S. Moreover, transient eddy processes dominate over stationary eddy fluxes of momentum and heat at both latitudes. This last point, in addition to the strong acceleration produced by the Coriolis force in the entrance region of the SPCZ jet, provides the motivation to examine the maintenance of the time–mean westerlies using the localized E–P flux formulation.

The upper two panels of Fig. 5 illustrate the two terms in the transformed momentum equation most relevant to the present investigation: the total E–P flux divergence and the Coriolis term. The third panel in Fig. 5 shows the sum of the two quantities depicted in the top two panels, while the bottom panel gives the total residual of (8). Unlike any other Southern Hemisphere subtropical region during the SOP-1, Fig. 5a shows that transient eddies make a significant contribution in the SPCZ region to the balance of the momentum budget. In particular, the net effect of the eddies in the entrance region of the local jet is to decelerate the westerlies in excess of 15 m s^{-1} day^{-1}. This is primarily the result of eddy momentum flux divergence. In the jet exit region, the eddies are acting to produce an acceleration over 15 m s^{-1} day^{-1} at 26°S, 160°W. Moreover, both the horizontal (barotropic) and vertical (baroclinic) components (not shown) are contributing to this acceleration, with the contribution by the latter being slightly larger. In essence, then, it appears as though the net effect of the transient eddies is to move the local jet eastward. The reason for the strong acceleration in the exit region can be explained by the fact that most of the cyclones present during period 1 not only originated within the cloud band near 160°W,

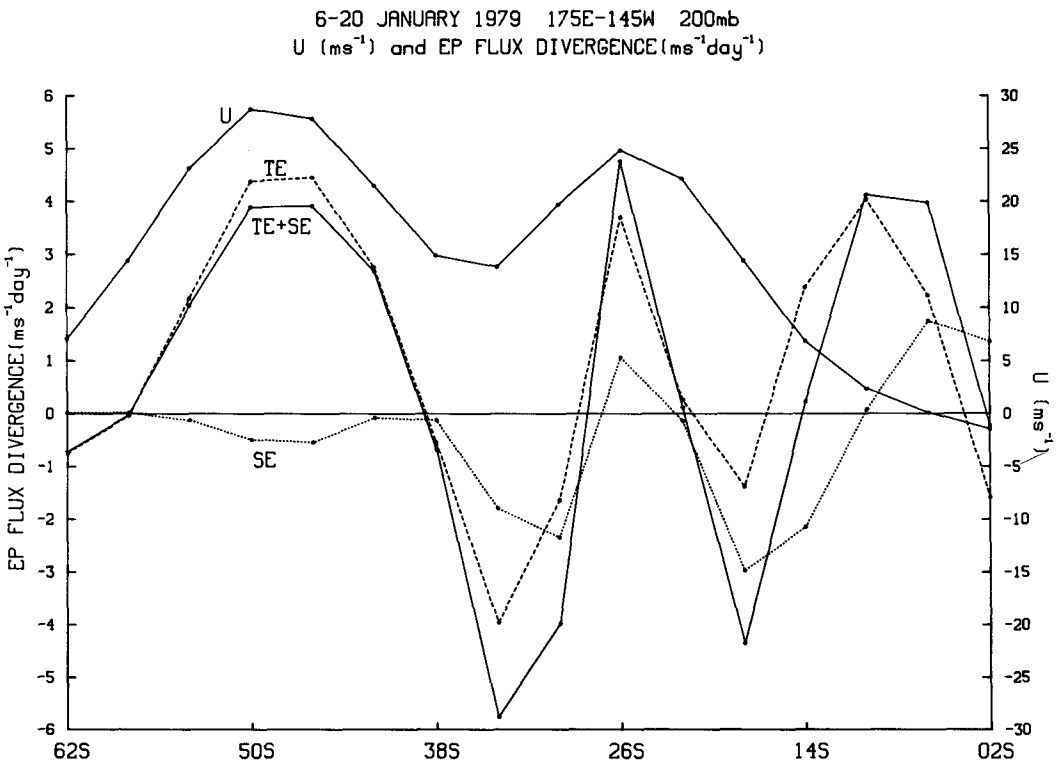

FIG. 4. Meridional distributions at 200 mb of the zonal wind component in m s^{-1}, total zonal E–P flux divergence in m s^{-1} day^{-1} (solid line), and E–P flux divergences due to transient eddies (dashed) and stationary eddies (dotted), averaged from 175°E–145°W.

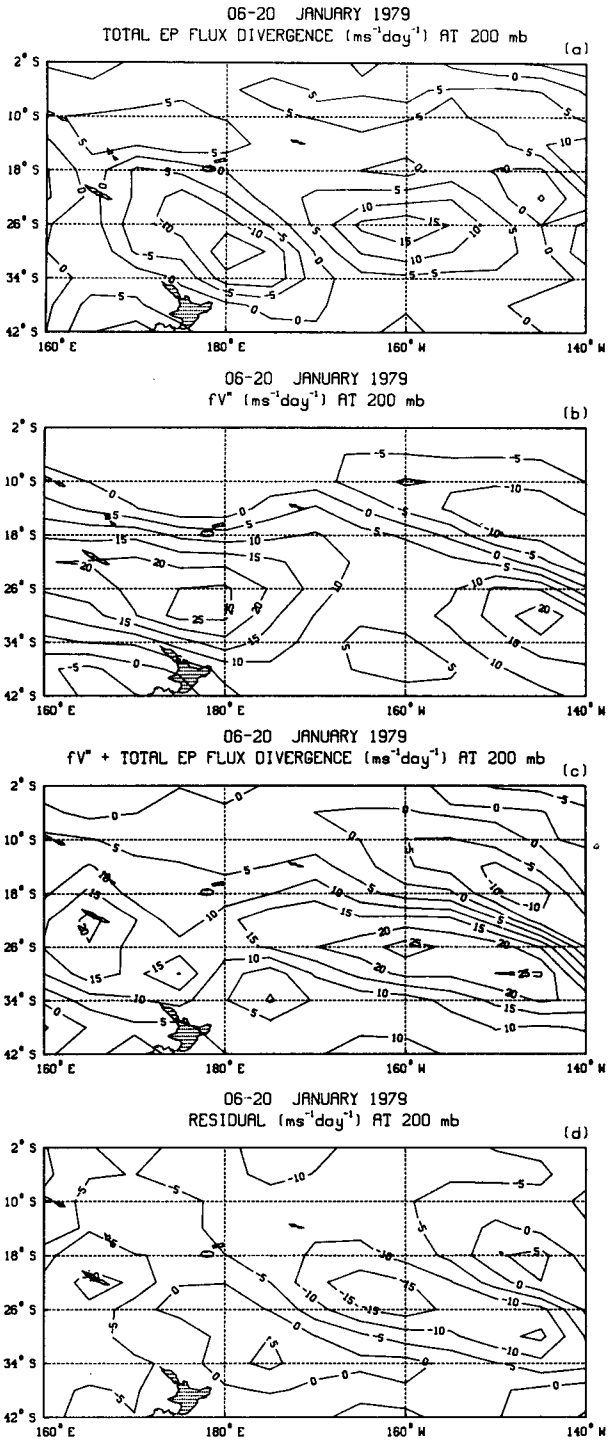

FIG. 5. (a) Total zonal E–P flux divergence, (b) Coriolis force due to the "residual" meridional circulation, (c) sum of (a) and (b), and (d) residual term, F_x, in (8). All contributions are in m s^{-1} day^{-1}.

but remained nearly stationary for several days. In fact, several of the cyclones spent their lifetimes in this region. Others propagated very rapidly along the diagonal portion of the SPCZ toward middle latitudes (Vincent 1985).

The tendencies due to the Coriolis term are presented in Fig. 5b. An acceleration of more than 25 m s^{-1} day^{-1} is seen in the SPCZ jet entrance region, and positive accelerations are evident everywhere to the south of the cloud band where the residual meridional wind is directed poleward. As such, the Coriolis term offsets the deceleration by the eddy momentum flux divergence in the jet entrance region, but enhances the acceleration produced by the transient eddies in the jet exit region. The importance of both terms in maintaining the time-mean westerly jet is clearly shown by their sum in Fig. 5c. It is also interesting to note that along the diagonal portion of the SPCZ, where transient eddies are playing an important role, the magnitude of v^* is slightly less than the magnitude of v_χ (Fig. 3). This probably indicates that the eddies themselves are inducing a small meridional divergent circulation, which helps to contribute to the total v_χ field. Of course, this effect is contained within the divergence of the E–P flux vector (Fig. 5a). In addition, as stated earlier v^* cannot be assumed to be entirely independent of the effects of the eddies in this region. Certainly, the eddies are highly interactive with the diabatic heating and it is not possible to totally isolate these processes. It is with this point in mind that Trenberth (1986) notes that one of the major shortcomings of the E–P flux approach is that eddy moisture transports and the organized release of latent heat by eddies (e.g., Salustri and Stone 1983) are not included as an eddy effect in the transformed equations. Rather, only the total diabatic heating is specified [Eq. (A11), Trenberth].

The residual of all terms in the transformed momentum budget represents the effects of friction, the transfers of momentum between the grid scale and the subgrid scale, and the cumulative effects of errors from other terms. Figure 5d shows that a general balance exists, except in the SPCZ jet exit region where the transient eddies are important and the Coriolis term plays a complementary role. Trenberth discusses at length that his results sometimes showed large imbalances (i.e., large residuals) at certain locations in the Southern Hemisphere tropics and subtropics. He suggested that residuals on the same order as other terms in (8) appeared to be unrealistic and were the result of errors in the observational analyses. Certainly, any study that utilizes real data also utilizes imperfect data, and even for the comprehensive observations compiled during FGGE there are substantial uncertainties in the analyses (e.g., Paegle et al. 1983; Lau 1984). Furthermore, these uncertainties are greatest on the smaller scales and are magnified when divergences are computed. For this reason, the magnitude of the terms presented in Fig. 5 should certainly be interpreted with caution. Nonetheless, it should be noted that the large residual found in the exit region of the SPCZ jet (Fig.

5d) is also not inconsistent with results from other studies that have inferred large free atmosphere sinks of momentum and energy by eddy dissipative processes in regions of maximum cyclone activity (e.g., Kung 1969; Smith and Adhikary 1974). This can be especially true in the upper troposphere near jet cores where wind shears are maximized (e.g., Kung 1966; Smith 1980). Thus, we conclude that although the residual of (8) may reflect uncertainties in the FGGE analyses, it may also represent an eddy exchange of momentum and energy to smaller, undetectable scales of motion.

c. *Rotational and divergent energetics*

The previous results have emphasized the good correlation observed in the summer hemisphere between regions of maximum poleward-moving divergent outflow and the formation and propagation of nearby subtropical westerly maxima. Since the westerly maxima are largely accounted for by the rotational component of the wind, this implies that at least a portion of the divergent kinetic energy associated with the outflow is being converted to support the rotational kinetic energy maxima in the subtropics. An ideal tool to investigate the magnitude of this conversion is the rotational and divergent energetics technique described in section 2. Surprisingly, this technique has not been applied to the problem of jet stream maintenance except for the limited study of Chen et al. (1988). They used the open domain budgets to study the forcing of the seasonal-mean Northern Hemisphere wintertime jet cores. Their results showed a counterbalance between $G(k_\psi)$ and HFR(k), with the former (latter) positive in the entrance (exit) regions of the jets. Moreover, they found that $G(k_\chi)$ and $C(k_\chi, k_\psi)$ were also positive (negative) in the entrance (exit) regions, but were smaller and more important at lower latitudes. This result is in agreement with Blackburn (1985) and Trenberth and Chen (1988) and suggests that although tropical outflow does contribute to the maintenance of the local wintertime seasonal jet cores (e.g., Krishnamurti 1979), the primary contribution resides in the rotational budget itself.

Figure 6 illustrates the area-averaged 200-mb rotational and divergent kinetic energy budgets for period 1 over the South Pacific and western Indian oceans. Note that the averages are computed over the latitudes of the subtropical westerly maxima (i.e., 18°–34°S). For the South Pacific region, the main source of k_χ is seen to be $G(k_\chi)$. Physically, this occurs via downgradient divergent flow from the heating maximum into the region of the westerly maximum. Much smaller contributions are made by the horizontal and vertical flux divergences of total kinetic energy by the divergent wind, although both are positive. The important point is that the primary balance occurs through $C(k_\chi, k_\psi)$, indicating that much of the divergent kinetic energy

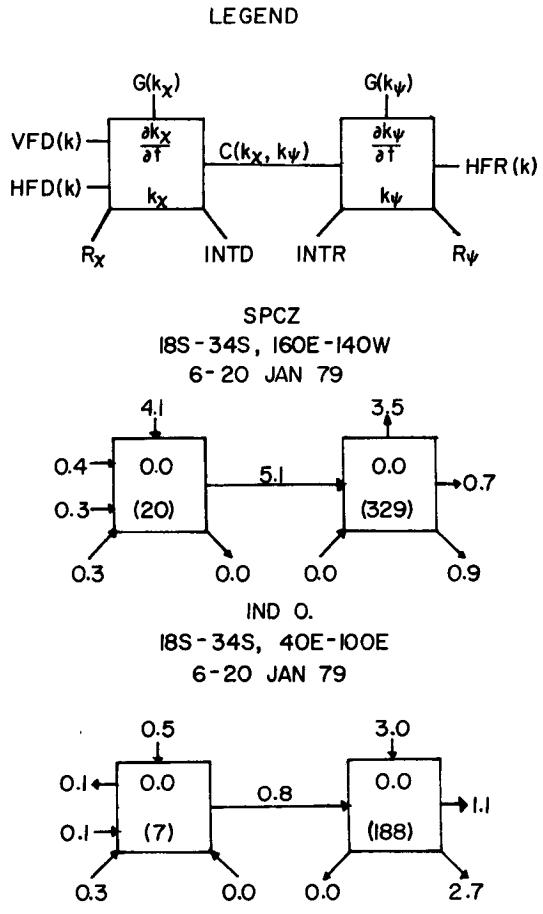

FIG. 6. Rotational and divergent components of the energy budget at 200 mb for the SPCZ and Indian Ocean regions. Contents are in $m^2\ s^{-2}$ and others are in $10^{-3}\ m^2\ s^{-3}$.

generated in the SPCZ is converted to support the westerly jet. This point becomes even more evident when the k_ψ budget is examined. Here, it is seen that $G(k_\psi)$ is actually negative, a result of supergeostrophic flow through the pronounced trough/ridge system near the IDL associated with the cloud band (Huang and Vincent 1983). Moreover, even though both HFR(k) and the residual are negative, $G(k_\psi)$ is the major sink of k_ψ. When these results are taken together, plus the fact that $k_\chi \ll k_\psi$, the importance of the divergent outflow to the maintenance of the westerly maximum is clear. To contrast these results to a region with much less convection, the western Indian Ocean energy budget is also shown in Fig. 6 for period 1. Note the substantially smaller values of $G(k_\chi)$, $C(k_\chi, k_\psi)$, and k_ψ.

The spatial distributions of $G(k_\chi)$ and $C(k_\chi, k_\psi)$ at 200 mb for period 1 are shown in Fig. 7. Values of both terms ≥ 2.5 ($10^{-3}\ m^2\ s^{-3}$) are shaded. Several interesting features are apparent. First, an excellent agreement is seen in both the magnitude and spatial distribution of $G(k_\chi)$ and $C(k_\chi, k_\psi)$. As implied by Fig.

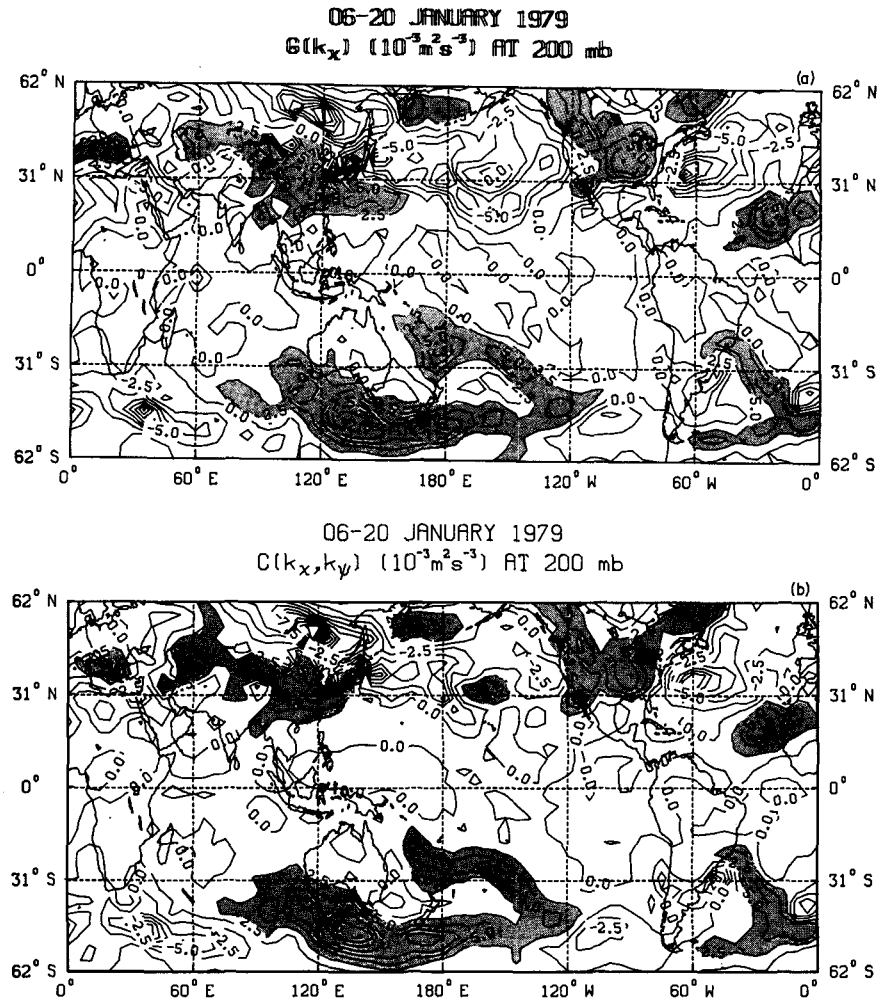

FIG. 7. (a) Generation of divergent kinetic energy at 200 mb in 10^{-3} m^2 s^{-3} and (b) the same as (a), except for the conversion from divergent to rotational energy. Values $\geq$ 2.5 are shaded.

6, this shows that nearly all of k_x generated by downgradient divergent flow is converted to support k_ψ. Second, the extent to which the divergent flow is supporting the subtropical westerly maxima in the Southern Hemisphere is clearly demonstrated. For example, large values of both terms are evident over the SPCZ westerly jet, as well as in association with the westerly maximum over the coast of Brazil. Likewise, during period 2 (not shown), the largest positive values of both terms are found over the western Indian Ocean and between Australia and New Zealand, two regions where the westerlies increased by more than 15 m s^{-1} (see Fig. 4c in HV). Moreover, it appears as though the strong convection over Indonesia and the SPCZ helps to maintain the higher-latitude westerly maximum south of Australia. This is also in good agreement with the distribution of fv_x shown in Fig. 2. Finally, it is important to note that the distributions of $G(k_x)$ and $C(k_x, k_\psi)$ in the Northern Hemisphere jet stream regions are very similar to those presented by Chen et al. (1988). In particular, positive values are seen in the jet entrance regions, while values in the exit regions are negative. More importantly, these terms are found to be considerably smaller than $G(k_\psi)$ and HFR(k) (not shown), although their distribution is similar.

4. Summary

The purposes of the present investigation have been to extend the analyses of HV and quantitatively determine the extent to which divergent circulations interact with, and accelerate, the summer subtropical westerlies and to examine the roles of other local forcings on the observed wind maxima. Although calculations were performed over the entire SOP-1 of FGGE, results were focused in this article on one subperiod, namely, 6–20 January 1979. It was found that maximum values of v_x at 200 mb were not only located near the entrance regions of the maximum subtropical westerlies, but that v_x accounted for nearly all of the

total ageostrophic meridional wind in the Southern Hemisphere subtropics. In contrast, the primary components of v_a in the latitudes of the stronger Northern Hemisphere subtropical jets were largely rotational. This agrees with the findings of Blackburn (1985) and Trenberth and Chen (1988) and suggests, at least for this case study, that tropical divergent circulations play a much greater role in the direct forcing of local summertime subtropical westerlies than in the forcing of local wintertime jet streams. For the zonally averaged circulation, however, it should be remembered that $f[v_a] = f[v_x]$ so that the same conclusion cannot be drawn. In this case, the zonal momentum budget reveals that the wintertime midlatitude westerlies are largely maintained by the convergence of eddy westerly momentum, while the Coriolis torque acting on the upper branch of the Hadley cell maximizes at slightly lower latitudes.

The above results for the maintenance of local westerly maxima were emphasized in the current study through an analysis of the complete divergent and rotational kinetic energy budgets. In particular, it was shown that nearly all of k_x generated by downgradient divergent flow was converted to support k_ψ. More importantly, unlike the winter hemisphere, it was found that the generation of k_x and the conversion to k_ψ were the dominant budget terms in the Southern Hemisphere subtropics, again illustrating that westerlies in these latitudes were principally maintained by the divergent circulations.

The importance of all forcing terms in the complete momentum budget was examined through an application of the localized E–P flux equations (Trenberth 1986). In particular, we examined the impact of eddy sensible heat and momentum transports on the westerly maximum near the SPCZ, a region of maximum cyclogenesis in the tropics. It was shown that transient eddies were decelerating the flow in the entrance region of the SPCZ jet through momentum flux divergence, and this helped to offset the strong acceleration by the Coriolis force applied to the diabatically driven "residual" meridional wind. In the exit region, however, the net effect of the eddies was to strongly accelerate the jet. Although the magnitude of the contributions of the individual terms in the transformed momentum equation has to be interpreted with caution because of errors in the FGGE analyses, it appeared that eddy dissipation processes may have accounted for much of the remaining time–mean momentum balance in the SPCZ region.

The findings here are limited in that they encompass only the SOP-1 of FGGE. The interactions of divergent and rotational flows in the summertime subtropics may not be as well defined as they were in our case study for other time periods, and the results discussed here could be different for a longer-term mean such as the summer season as a whole. Presently, we are extending our diagnostic analyses to include routine datasets over longer time periods. Nonetheless, taken with the results presented in HV, we have shown that important deviations in tropical heating can occur over relatively short time periods, and that corresponding changes in the meridional divergent wind can strongly affect local subtropical rotational flows. This finding has important practical applications. Finally, we have attempted to utilize several new analysis tools that have not received wide attention in the literature. Certainly their potential applications are not limited to the type of study presented here, and we feel that they can make a significant contribution to future diagnostic and model studies of the general circulation.

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