NOTES AND CORRESPONDENCE

Observations of the Final Warming in the Stratosphere of the Southern Hemisphere during 1979

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ABSTRACT

The evolution of the flow in the Southern Hemisphere during the period 31 August–10 November 1979 is examined. The final stratospheric warming of 1979 and the associated reversal of the flow above 10 mb occurred during this period. It is found that this warming process was nearly monotonic, but modulated by a series of events with enhanced eddy activity.

1. Introduction

Major midwinter stratospheric warmings are a feature of the Northern Hemisphere climatology, although not observed in the Southern Hemisphere. This has been partly attributed to differences in the distributions of zonal-mean wind. During the winter, winds in the lower and middle stratosphere are much stronger in the Southern Hemisphere than in the Northern Hemisphere (e.g., Hamilton, 1982; Hartmann *et al.*, 1984). This is also the case for the lower stratosphere during spring. Therefore, we can expect differences in the transition from winter to summer circulations in the stratosphere of the two hemispheres.

Phillpot (1969) shows a series of geopotential fields at 30 mb during the period 16 August–30 November 1967. The typical wintertime circulation with a circumpolar vortex changed during that period to a pattern that consisted of two weak well-separated cyclonic vortices. He also shows a series of temperature fields at 30 mb during October 1968 that reveal a general warming trend at that level, and the migration of the location of maximum temperature.

In this paper, we examine the evolution of the flow in the Southern Hemisphere during the period when the final stratospheric warming and the associated reversal of the flow above 10 mb occurred in 1979. We begin by describing the data and the evolution of the flow in Sections 2 and 3, respectively. In Section 4 we use the Eliassen-Palm diagnostics to relate eddy activity with changes in the mean flow.

2. Data

The dataset for this study consists of the U.S. National Meteorological Center (NMC) 1200 GMT analysis of temperature and geopotential fields between 1000 and 0.4 mb for the period 31 August–10 November 1979.

The NMC fields for 1979 were obtained on a 65 $\times$ 65 polar stereographic grid and interpolated to a 2.5° lat by 5° long grid. Missing fields in the time series were replaced with those obtained by linear interpolation between the closest available fields before and after the missing date. The pressure levels used in this study were 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 10, 5, 2, 1, and 0.4 mb. Winds were obtained from the geopotential fields by using the geostrophic relations.

3. Evolution of the flow

The time evolutions of zonal-mean (geostrophic) wind and temperature at 2 and 10 mb during the period 31 August–10 November are shown in Figs. 1 and 2, respectively. During the early part of the period the stratospheric jet at both levels was centered at about 60°S, and was decelerating rapidly. The jet was stronger at 10 mb than at 2 mb. Consistently, at the latter level, the temperature in the polar region was higher than in middle latitudes. Towards the end of September, easterlies appeared at 10 mb in low latitudes. Rapid changes in the stratospheric circulation occurred during mid-October. There was an acceleration of the flow followed by a rapid deceleration in high latitudes, and a simultaneous warming of the polar region. After these events, easterlies appeared at 2 mb south of approximately 30°S, and the temperature in the polar region became higher than in midlatitudes at 10 mb. Toward the end of the period 31 August–10 November there were east-

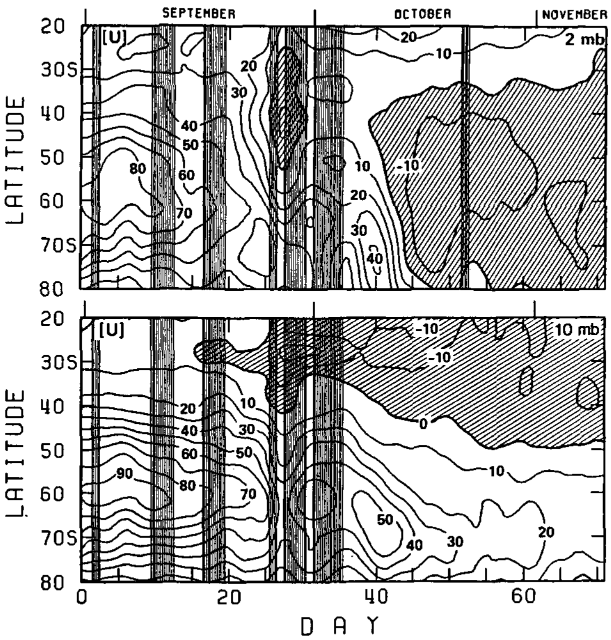

FIG. 1. Zonal mean geostrophic wind (m s^{-1}) at 2 and 10 mb during the period 31 August–10 November 1979. Vertical lines indicate times when data are missing from the record.

erlies in middle and high latitudes at 2 mb, and in low latitudes at 10 mb. The deceleration at 10 mb in high latitudes continued gradually, so that in approximately 10 days after the end of the period there were easterlies for all latitudes at this level.

A series of latitude–height cross sections of zonal-mean wind for the subperiod of rapid changes during mid-October is shown in Fig. 3. On 6 October the stratospheric jet core was at about 60°S, 30 mb and there were easterlies in the lower-subtropical and upper-polar stratosphere. From 6 to 10 October the jet increased in intensity, and shifted poleward and upward. The easterlies in the upper polar stratosphere disappeared and the region of easterlies extended upward and poleward from the lower subtropical stratosphere. From 14 to 18 October, these easterlies increased in intensity and extended farther down. At that time, the summer circulation replaced the winter circulation above 5 mb.

A series of geopotential height fields for 2 and 10 mb during the same subperiod is shown in Fig. 4. On 6 October the patterns at both levels consisted of a cyclonic vortex with strong cross polar flow, and an anticyclonic vortex south of Australia. From 6 to 10 October, the cyclonic vortex shifted toward the pole at both levels. From 10 to 14 October, the low at 2 mb weakened and moved away from the pole while the high intensified over the Indian Ocean sector. At 10 mb, on the other hand, the low weakened slightly and the high moved westward. From 14 to 18 October, the low at 2 mb weakened in the Pacific sector, while the high occupied the polar region. At 10 mb there were no significant changes during those four days.

The evolution of the temperature field for 2 and 10 mb during the same subperiod is shown in Fig. 5. The maximum temperature was over the polar region at all times. After an initial cooling, there was a polar warming which was particularly noticeable at 10 mb, where the temperature increased 20 K from 10 to 18 October. In high latitudes, a zonal wavenumber 2 pattern was apparent at 2 mb, particularly at the beginning of the subperiod, while a wavenumber 1 pattern prevailed at both levels during later times, particularly on 14 October.

Longitude–time plots of the zonal wavenumbers 1 and 2 components of the geopotential height field at 60°S, 10 mb are shown in Fig. 6. At the beginning of the subperiod from 6 to 18 October (days 37 to 49), both wavenumbers 1 and 2 had large amplitudes. Wavenumber 1 decayed without a significant change in phase, and later amplified and maintained large amplitude while slowly moving eastward. Wavenumber 2 decayed while moving eastward, and maintained small amplitude without a significant change in phase during the remainder of the subperiod.

The zonal mean northward eddy heat flux at 2, 50 and 850 mb is shown in Fig. 7. The relative maxima in poleward flux at 2 mb seem to be correlated with others that occurred a few days earlier at lower levels. The eddy activity at 2 mb decreased considerably a few days after the easterlies were established at that level. The zonal mean northward eddy momentum

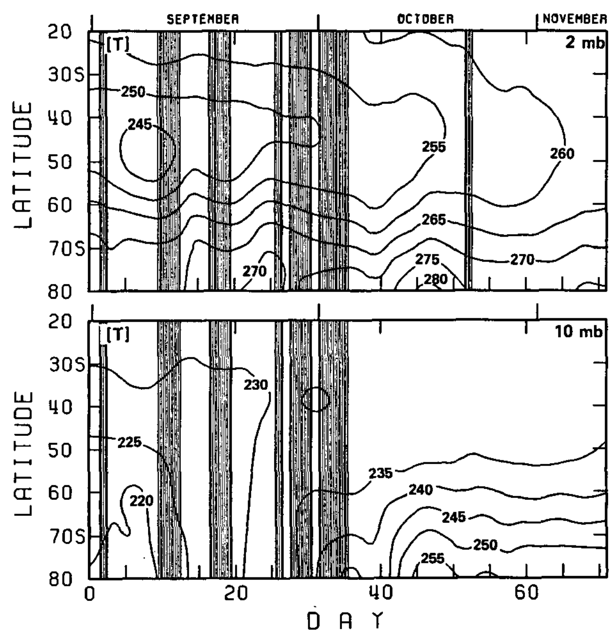

FIG. 2. As in Fig. 1, except for temperature (K).

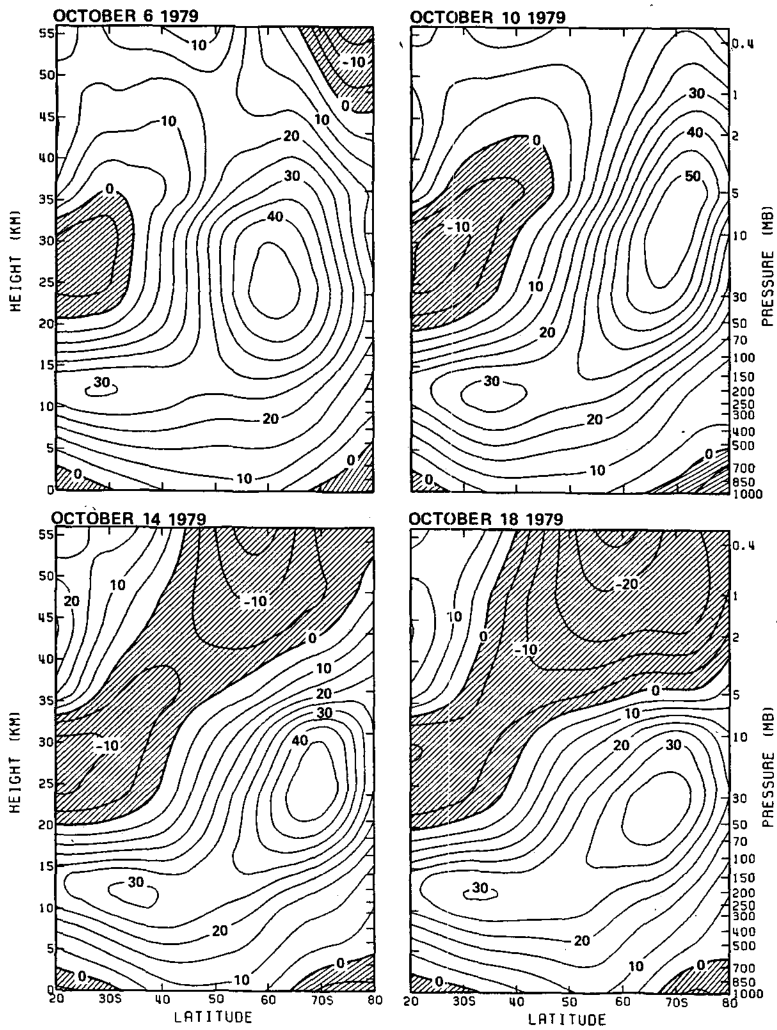

FIG. 3. Zonal-mean geostrophic wind (m s^{-1}) for selected dates during the subperiod 6–18 October 1979.

flux at 2, 10, and 300 mb is shown in Fig. 8. A comparison between Figs. 7 and 8 indicates that, at 2 mb, enhanced eddy heat flux was generally simultaneous with enhanced momentum flux. An interesting exception occurred during the subperiod 6–18 October. The eddy momentum flux divergence was well-correlated with the zonal mean flow deceleration during this subperiod.

4. Diagnostics of wave-mean flow interactions

We use the transformed Eulerian mean diagnostic equations (Andrews and McIntyre, 1976; Edmon *et al.*, 1980; Palmer, 1981) to characterize wave-mean flow interactions. The Eliassen-Palm (E-P) flux vector, defined by

$$\mathbf{F} = \rho_0 a \cos\phi(-\overline{u'v'}, f\overline{v'\theta'}/\bar{\theta}_z), \qquad (4.1)$$

represents the direction of wave energy propagation. In (4.1) u and v are the zonal and meridional components of the horizontal velocity; θ is the potential temperature; $z = -H \ln(p/p_s)$ where H is the scale height (7 km) and p_s is a reference pressure (1000 mb); $\rho_0(z) = \rho_s \exp(-z/H)$ where ρ_s is a reference density; f is the Coriolis parameter; and a is the radius of the earth. Overbars represent zonal averages while primes represent deviations from those averages. The divergence of the E-P flux vector ($\nabla \cdot \mathbf{F}$), which is related to the northward potential vorticity flux, appears in the transformed Eulerian mean momentum equation

$$\partial_t \bar{u} - f\bar{v}^* - \bar{\mathcal{F}} = \nabla \cdot \mathbf{F}/(\rho_0 a \cos\phi) = \mathrm{DF}, \qquad (4.2)$$

where ϕ is latitude and $\bar{\mathcal{F}}$ is the subgrid scale momentum source. The meridional component of the residual mean circulation is given by

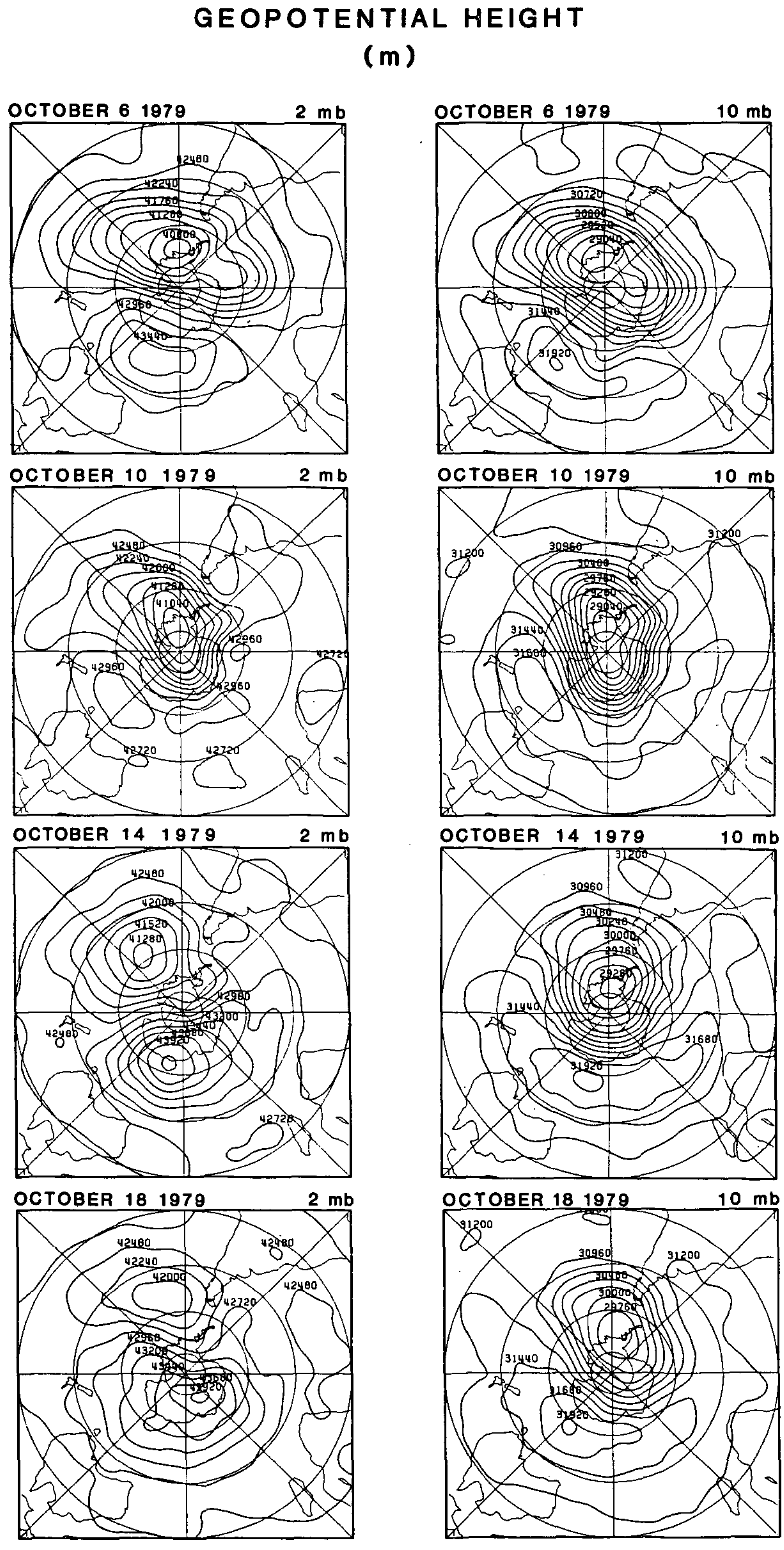

FIG. 4. Geopotential field (m) at 2 and 10 mb for selected dates during the subperiod 6–18 October 1979.

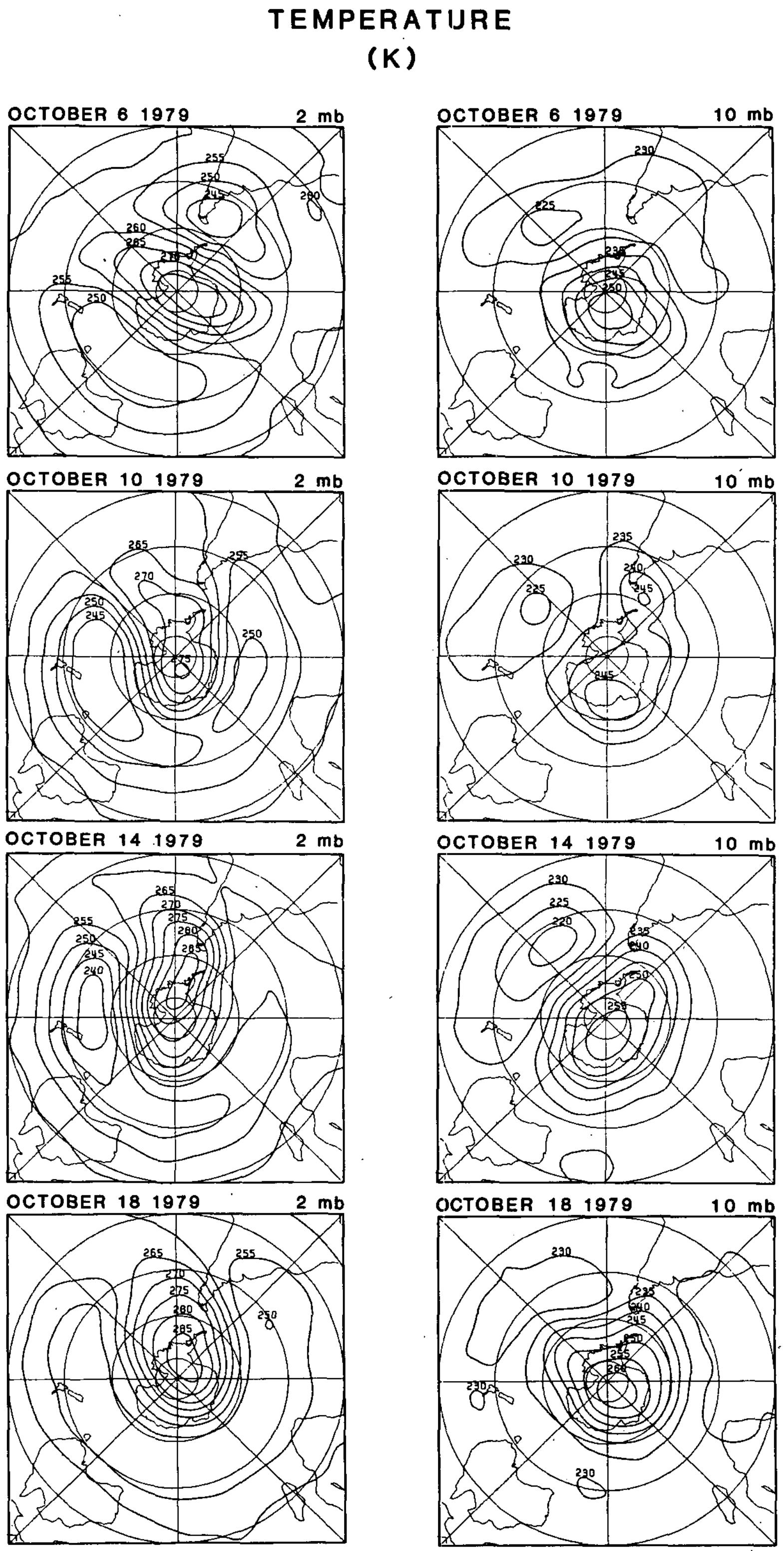

FIG. 5. As in Fig. 4, except for temperature (K).

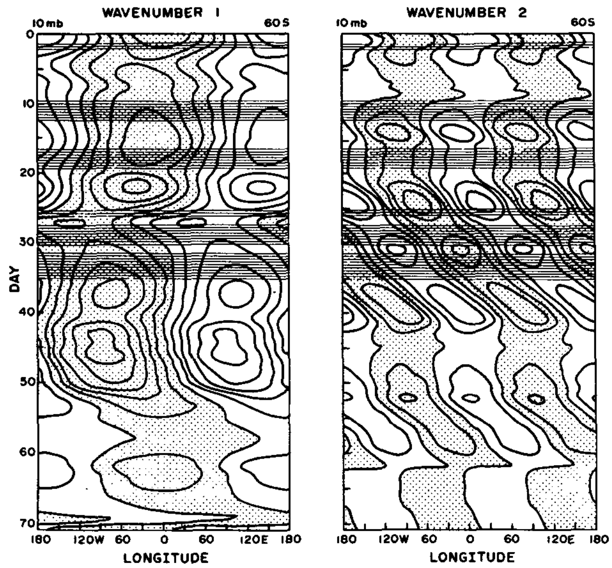

FIG. 6. Longitude–time plots of the zonal wavenumbers 1 and 2 components of the geopotential height field at 60°S, 10 mb. The contour interval is 200 m; negative values are shaded.

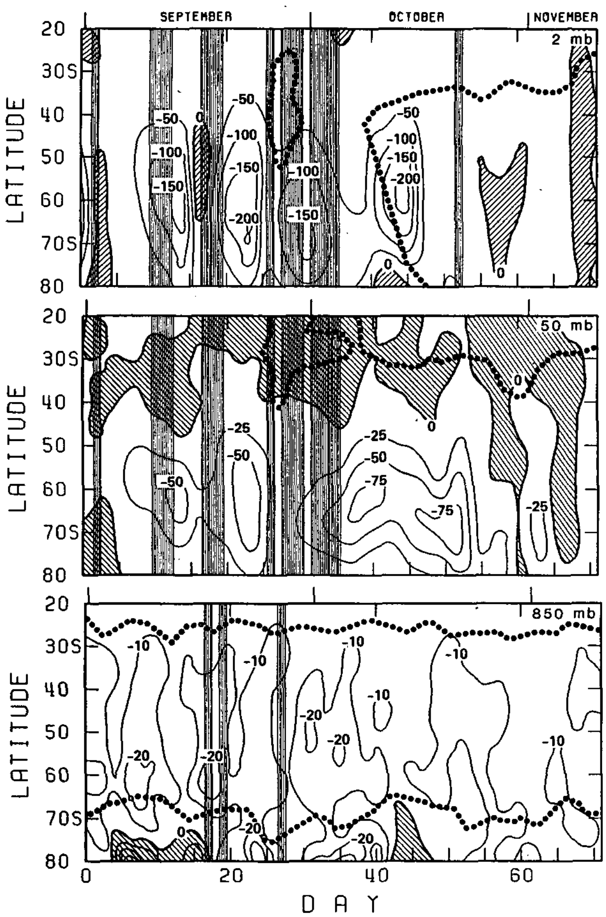

FIG. 7. As in Fig. 1, except for northward eddy heat flux (m s^{-1} K) at 2, 50 and 850 mb. The thick dotted lines indicate zero zonal-mean wind.

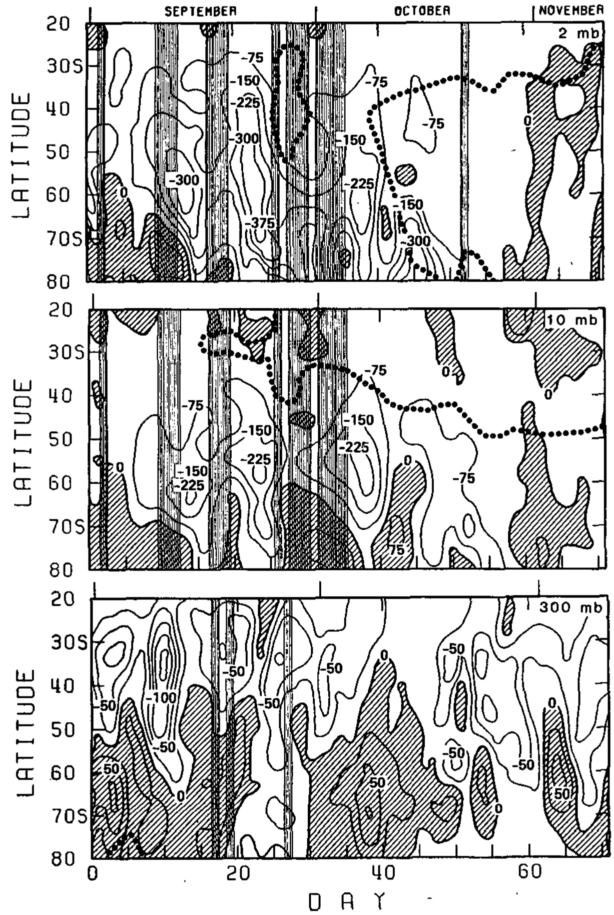

FIG. 8. As in Fig. 7, except for eddy momentum flux (m^2 s^{-2}) at 2, 50 and 300 mb.

$$\bar{v}^* = \bar{v} - \frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0\overline{v'\theta'}/\bar{\theta}_z). \tag{4.3}$$

A series of E-P cross sections during the subperiod 6–18 October are shown in Fig. 9. In these plots the length of E-P flux vectors has been multiplied by 10 between 100 mb and 5 mb, and by 100 above this level. On 6 October, E-P fluxes in the stratosphere north of 60°S were nearly equatorward and largest in middle latitudes. These large fluxes had relatively strong divergence around 60°–70°S and convergence around 35°–45°S. This convergence was associated with the extension of the easterlies from the subtropics to midlatitudes that occurred at that time. Upward directed E-P fluxes were the distinctive feature of the middle and lower troposphere at middle latitudes. There was strong E-P flux convergence in the upper troposphere at high latitudes. On 10 October, E-P fluxes in the stratosphere were more vertical than four days earlier. In particular, they were upward and large in the lower stratosphere about 50°–70°S. Although weakly defined, the stratospheric dipole pattern of E-P flux convergence at middle latitudes and

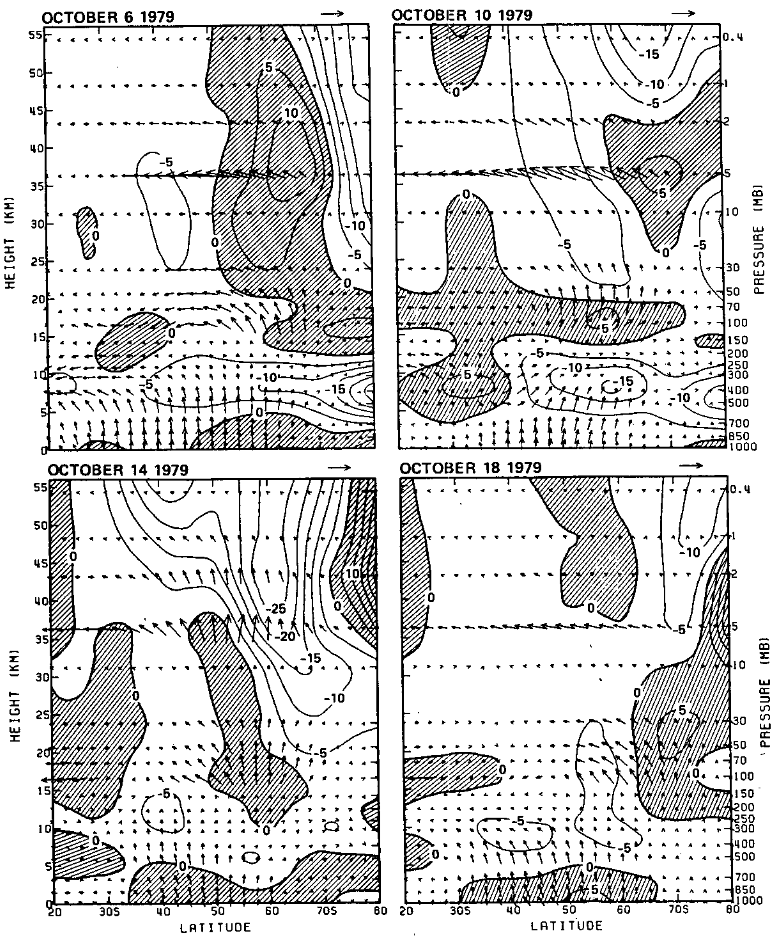

FIG. 9. **F** (reference arrow: 10^{16} kg m s^{-1}) and DF (m s^{-1} day^{-1}) for selected dates during the subperiod 6–18 October 1979.

divergence at high latitudes which was a persistent feature during the winter of 1979 (Hartmann *et al.*, 1984) still existed at that time. The E-P fluxes in the upper troposphere were poleward south of about 40°S. On 14 October, E-P fluxes throughout the atmosphere at middle latitudes were large and upwards. A broad region with the strongest E-P flux convergence for the subperiod was apparent in the middle and upper stratosphere. The strong convergence was associated with the large decelerations observed at that time for both 2 and 10 mb (see Fig. 1). On 18 October, E-P fluxes in the stratosphere at middle latitudes were again equatorward, and their convergence was weak.

The zonal-mean wind acceleration, DF and the contributions to DF by zonal wavenumbers 1 and 2 for 60°S, 2 mb and 70°S, 2 mb during the subperiod 6–31 October are shown in Fig. 10. At 60°S, the eddies had a strong decelerating effect in mid-October which was partially compensated by the residual mean meridional circulation. The contributions to DF by wavenumbers 1 and 2 were comparable in magnitude at that time. Decelerations and eddy effects were weak during the second half of October. At 70°S, the eddies had an accelerating effect at the beginning of the subperiod. The contribution of wavenumber 1 was dominant for the fluxes at that time. The eddies had a decelerating effect during mid-October, and the residual mean meridional circulation also contributed to the deceleration at about 13 October. The contributions of wavenumbers 1 and 2 were generally opposite to each other at this time. Decelerations and eddy effects were small toward the end of October.

5. Conclusion

We have studied the observed evolution of the flow in the Southern Hemisphere during the period 31 August–10 November 1979. The transition from westerly to easterly flow above 10 mb occurred during this period. In general, such a transition developed gradually. However, it was considerably accelerated by wave-mean flow interactions during mid-October.

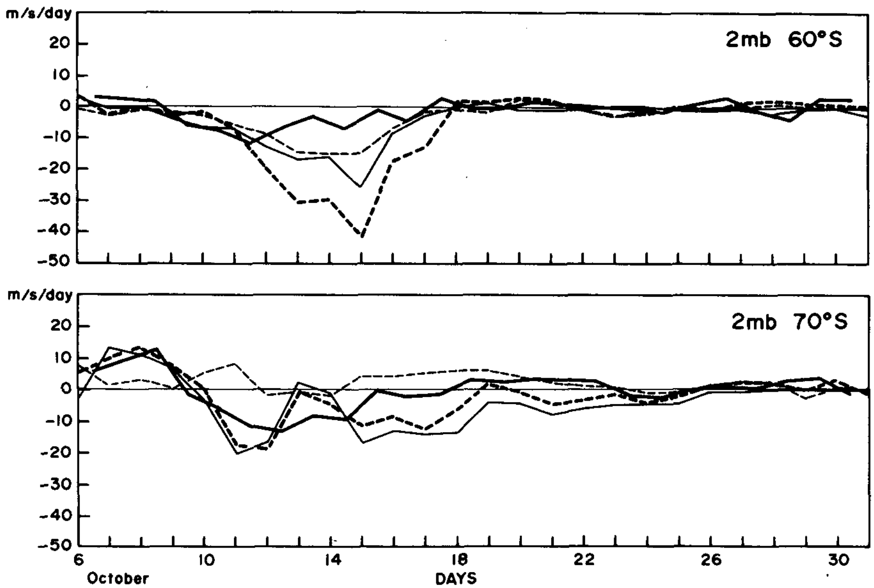

FIG. 10. Zonal-mean wind acceleration (thick-solid lines), DF (thick-dashed lines), and contributions to DF by zonal wavenumbers 1 and 2 (thin-solid and thin-dashed lines, respectively) for 60°S, 2 mb and 70°S, 2 mb during the subperiod 6–31 October 1979. Units are m s^{-1} day^{-1}.

We determined that the eddies were the dominant contributors to the strong deceleration of the stratospheric flow observed at that time.

These results, and those in the study by Hartmann *et al.* (1984) for the period May–September 1979, indicate that the evolution of the stratospheric circulation in the Southern Hemisphere during 1979 was nearly monotonic, but was sporadically modulated by a series of events with enhanced eddy activity.

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REFERENCES

Andrews, D. G., and M. E. McIntyre, 1976: Planetary waves in horizontal and vertical shear: The generalized Eliassen-Palm relation and the mean zonal acceleration. *J. Atmos. Sci.,* **33,** 2031–2048.

Edmon, H. J., Jr., B. J. Hoskins and M. E. McIntyre, 1980: Eliassen-Palm cross-sections for the troposphere. *J. Atmos. Sci.,* **37,** 2600–2616.

Hamilton, K., 1982: Some features of the climatology of the Northern Hemisphere revealed by NMC upper atmosphere analysis. *J. Atmos. Sci.,* **39,** 2737–2749.

Hartmann, D. L., C. R. Mechoso and K. Yamazaki, 1984: Observations of wave, mean-flow interaction in the Southern Hemisphere. *J. Atmos. Sci.,* **41,** 351–362.

Palmer, T. N., 1981: Diagnostic study of a wavenumber-2 stratospheric sudden warming in a transformed Eulerian-mean formalism. *J. Atmos. Sci.,* **38,** 844–855.

Phillpot, H. R., 1969: Antarctic stratospheric warming reviewed in the light of 1967 observations. *Quart. J. Roy. Meteor. Soc.,* **95,** 329–348.