*Tellus* (1990), *42A*, 41–50

# The role of transient eddies in low-frequency zonal variations of the Southern Hemisphere circulation

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(Manuscript received 7 November 1988; in final form 13 February 1989)

ABSTRACT

The dominant modes of low-frequency variation of the Southern Hemisphere (SH) circulation in winter have been identified using 15 years of monthly mean analyses of the SH troposphere. The two leading modes are primarily zonally-symmetric, representing out-of-phase variations of geopotential height between middle and high latitudes in one case and between the tropics and middle latitudes in the other. There are accompanying variations of zonal wind and temperature associated with these modes, which have an equivalent barotropic vertical structure in the extratropics. The two modes represent 25% of the variance of the monthly mean height in the SH. The high-latitude mode is also the dominant pattern of variation of 5-day average height anomalies, indicating that this is an important mode on time scales from about a week to a season. Using composites of monthly mean fields and transient eddy statistics for opposite extremes of this high latitude mode, the interaction between transient eddies and the anomalous mean flow is described. During one extreme of the variation, there is an increased height gradient, a stronger zonal jet and more baroclinicity at high latitudes. Although there may be some doubt about the reliability of the transient eddy statistics, they show an enhanced storm track at high latitudes, with transient eddy fluxes which help to maintain the anomalous mean flow.

## 1. Introduction

Over the past decade, there have been many studies of the low-frequency variations of the Northern Hemisphere (NH) circulation (e.g., Wallace and Gutzler, 1981; Esbensen, 1984; Barnston and Livezey, 1987), which have documented the typical modes of variation of monthly mean and seasonal mean NH geopotential height. Recently, Lau (1988) has described the principal modes of intermonthly variability of the NH winter transient eddy activity and found a strong relationship between variations of the transient eddy activity and the mean flow.

Relatively less attention has been paid to the low-frequency variations of the Southern Hemisphere (SH) circulation. Trenberth (1979), Mo and White (1985) and Kidson (1988) have shown that there are large amplitude variations of the zonal mean circulation in the SH on intermonthly and interannual time scales. Szeredi and Karoly (1987) and Szeredi (1987) have shown that the dominant modes of monthly variations of the SH circulation are primarily zonally-symmetric, involving opposing departures of height between middle and high latitudes in one case and between the tropics and middle latitudes in the other. The high latitude mode also has been found in analysis of variations on intermediate time scales (5–30 days).

Kidson (1988) has shown that the SH zonal mean westerly wind has a spectrum with large power at all low frequencies and significant peaks on seasonal and interannual time scales. The pattern of zonal mean wind variations is similar on synoptic to interannual time scales, with compensating departures at intervals of 20°

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latitude. The leading mode has opposing peaks at 40°S and 60°S and an equivalent barotropic structure. This is the same as the high latitude mode mentioned above. The regional pattern of height anomalies associated with this mode is zonally-symmetric poleward of 60°S but, in middle latitudes, the largest amplitudes are over the Indian and western Pacific Oceans. Kidson (1988) did not consider the variations of transient eddy activity associated with these low frequency variations of zonal wind in the SH.

Trenberth (1984) has contrasted the SH winter circulation during 1979, the year of the Global Weather Experiment and 1980. He showed that there were large differences in the zonal mean height and wind in middle and high latitudes. The pattern of these differences was very similar to the high latitude mode. Trenberth also contrasted the transient eddy activity between the two winters and showed that the anomalous westerly momentum flux convergence by the transient eddies was in the same region as the westerly anomalies in the mean flow.

Here, we describe a preliminary, but more general study of the rôle of transient eddies in the high latitude mode of low frequency zonal variations in the SH. Composite mean fields and transient eddy statistics for opposite extremes of this mode are contrasted. One extreme of the high latitude mode is associated with an enhanced height gradient, stronger zonal wind and more baroclinicity at high latitudes. This is accompanied by changes in the transient eddy statistics, including a poleward shift and enhancement of the storm track. The anomalous transient eddy fluxes help to maintain the anomalous mean flow.

## 2. Variations of the mean flow

Several studies have examined the low-frequency variations of the zonal mean SH circulation (Trenberth, 1979; Mo and White, 1985; Kidson, 1988) but they have not tried to assess the relative importance of zonally-symmetric and zonally-asymmetric variations. Using monthly mean station data, Szeredi and Karoly (1987) found that the leading modes of intermonthly variability in the SH are zonally-symmetric. In that study, the sparse and irregular station network in the SH may have meant that only the largest scale modes could be identified.

The following results, which show the importance of zonally-symmetric modes for intermonthly variations of the SH circulation, have been presented in more detail by Szeredi (1987). Monthly mean numerical analyses for the SH from the Australian Bureau of Meteorology for the period June, 1972 to March, 1987 have been used. The analysis methods and an assessment of the reliability of the analyses have been given by Le Marshall et al. (1985) and Karoly et al. (1986). Since the results for the zonally-symmetric modes are similar for both the summer and winter seasons, attention here shall be restricted to the SH winter season, defined to be the four calendar months, June to September.

Monthly anomalies were prepared for the 60 winter months over the 15 years. The data were available on a 5° latitude × 10° longitude grid poleward of 10°S, giving 577 gridpoints. The results were obtained using a reduced grid of 103 points, approximately equally-spaced with half the resolution of the full grid. The correlation matrix of monthly anomalies of 300 mb height on the reduced grid was computed. This level was chosen as the low frequency variations have large amplitude in the upper troposphere. A rotated principal factor analysis was performed on the correlation matrix to identify the different modes of variation. The results were compared using principal components and obliquely-rotated and orthogonally-rotated principal factors with variable numbers of factors rotated. The leading modes were very stable, having very similar structure using all the different methods.

The two leading modes are primarily zonally-symmetric, representing out-of-phase variations of height between middle and high latitudes in one case and between the tropics and middle latitudes in the other. These two modes explain 25% of the variance of monthly mean 300 mb height in the SH. They were also the leading modes of intermonthly variability of SH station data found by Szeredi and Karoly (1987). We shall concentrate on this high latitude mode in winter because the transient eddy activity is largest in middle and high latitudes and this mode has been described in other studies (Trenberth, 1984; Kidson, 1988). A more complete description of all the stable modes has been presented by Szeredi (1987).

The horizontal structure of the high latitude mode is shown in Fig. 1, together with the time series of the factor scores for this mode. There are variations of height of one sign poleward of about 60°S and opposite variations from 30°S to 55°S. This pattern is primarily zonally-symmetric but there are contributions from zonal wavenumbers one and three, giving the largest anomalous height gradients around 90°E, over the S. Indian Ocean. The factor time series shows marked intermonthly and interannual variations, as well as a negative trend. This trend may be associated with changes in data coverage and analysis methods over the period, as noted by Le Marshall et al. (1985).

Trenberth (1984) has described the differences in the SH winter circulation between 1979, the year of the Global Weather Experiment, and 1980. There was a much stronger height gradient and westerly jet at high latitudes in 1979 than in 1980, as shown by the change from negative scores for the high latitude mode in 1979 to positive scores in 1980 in Fig. 1. Also, the horizontal pattern for the high latitude mode in Fig. 1 is very similar to the height variations associated with fluctuations of the high latitude jet, shown by Kidson (1988) in his Fig. 8a.

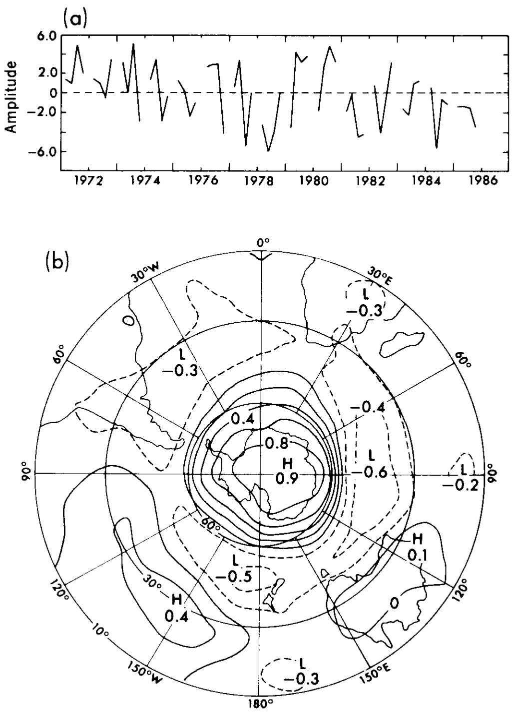


*Fig. 1.* (a) Time series of factor scores for the winter high latitude mode of 300 mb height (arbitrary units). Values for the 4 months in each winter season have been joined by straight lines. (b) Correlation between monthly anomalies of 300 mb height in winter and the factor time series in (a).

Composite mean fields for the high latitude mode were prepared by averaging the fields for the 8 months with the largest negative scores in the factor time series during the period 1977–83 (MIN, months listed in Table 1) and the 8 months with the largest positive scores (MAX, see Table 1). The composite zonal mean westerly wind for the extreme negative values (MIN) is shown in Fig. 2, together with the difference between the composites for the two extremes (MIN–MAX). The choice of sign for the differences is arbitrary but was made to emphasize the stronger westerly jet in the MIN composite. In this case, the composite zonal wind shows the climatological SH winter subtropical jet and an enhanced jet at high latitudes. There are westerly differences between the two composites of up to 8 m/s in the polar jet, with increased height and temperature gradients from 50° to 70°S. The vertical structure of the differences is equivalent barotropic, with increasing amplitude with height in the troposphere. These differences between the 8-month composites are comparable with the standard deviation of the monthly anomalies, indicating that they are significant.

As the high-latitude mode has a large barotropic component, it can be found in surface pressure variations. Trenberth and Christy (1985) have shown that the leading mode of interannual variations of global surface pressure is associated with this high latitude zonally-symmetric mode in the SH.

Kidson (1988) has shown that variations of the zonal mean westerly wind have increasing power but a similar horizontal structure from synoptic to interannual time scales. To determine the relative importance of zonally-symmetric variations at intermediate time scales and whether the horizontal structure is similar at shorter time scales, the analysis was repeated on five-day anomalies of 300 mb height for the SH winter. The data were obtained from daily SH analyses from the Australian Bureau of Meteorology for 10 winter

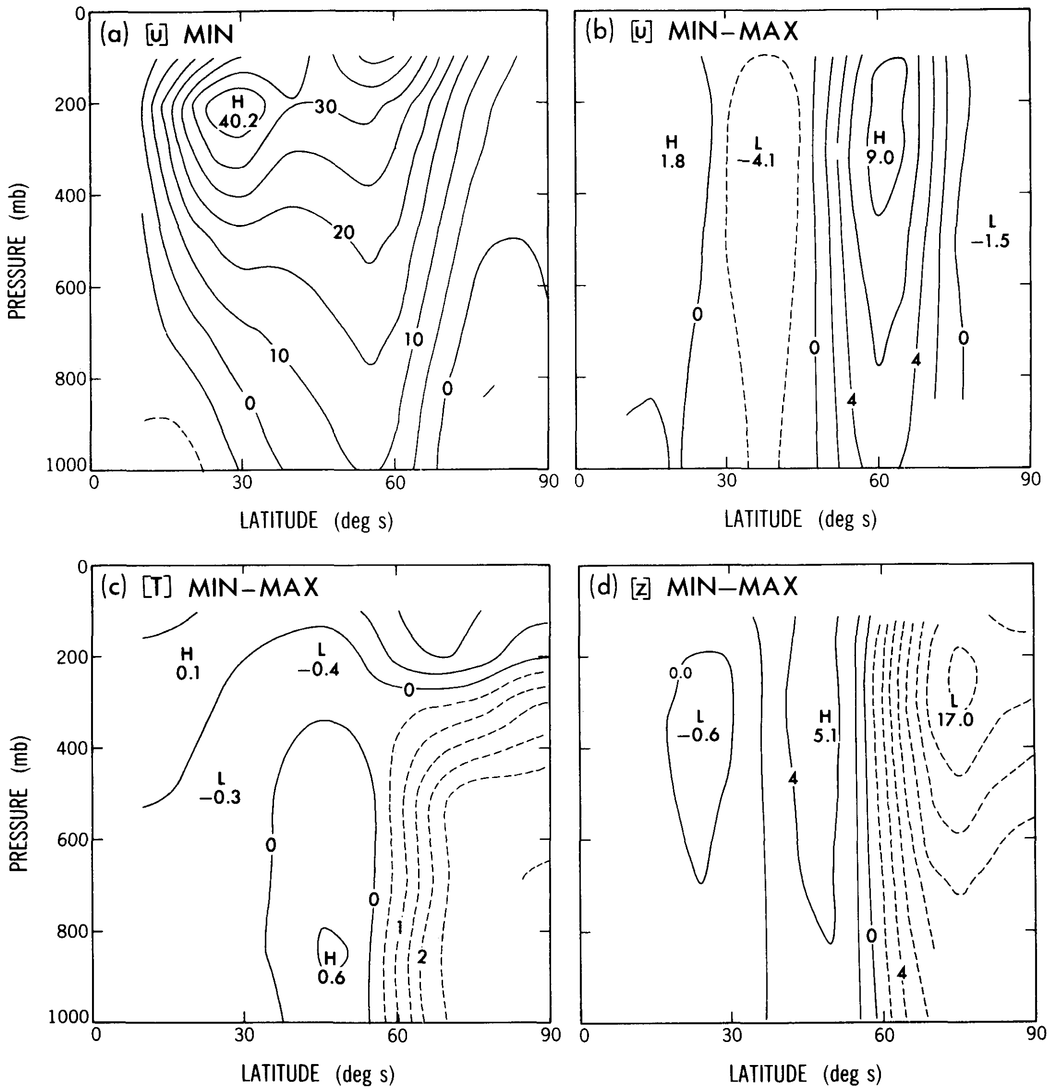


*Fig. 2.* (a) Composite zonal mean westerly wind (m/s) for 8 months of extreme negative values of the time series of the high latitude mode (MIN). (b) Difference of the zonal mean wind (m/s) between composites for opposite extremes of the high latitude mode (MIN–MAX). (c) As in (b) but for the difference of zonal mean temperature (°C). (d) As in (b) but for the difference of zonal mean height (dam).

seasons, each of 120 days in length from 1 June to 28 September, from 1978 to 1987. The 5-day average anomalies were computed as departures from the seasonal cycle for each individual winter, obtained by fitting a cubic to the daily height values in each winter. The cubic provides a continuous function through the four monthly means so the anomalies are like 5-day mean anomalies from the individual monthly means. This process passes variations with periods from about 10 to 60 days.

A rotated principal factor analysis was performed on these data in the same way as for the monthly anomalies. The high latitude mode was the leading factor but it explained a smaller fraction of the variance than for the monthly

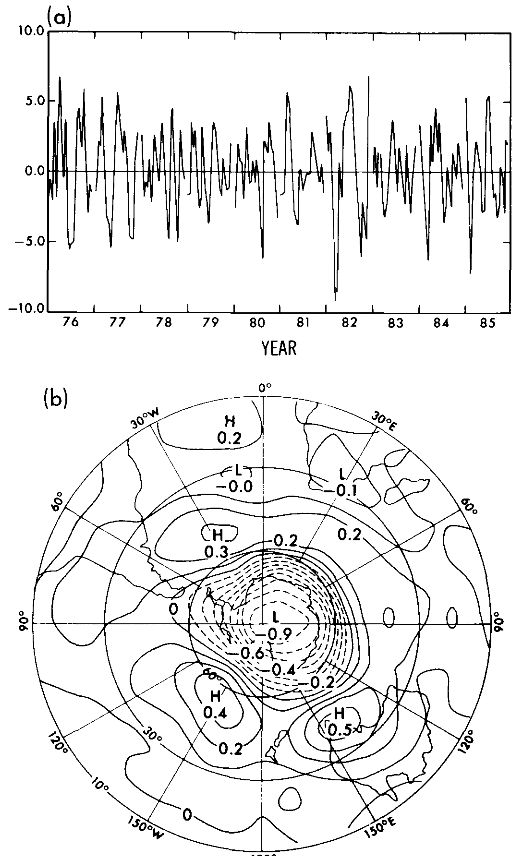


*Fig. 3.* (a) Time series of the leading rotated principal factor of 5-day average anomalies of 300 mb height in winter. Successive values in each winter have been joined by straight lines, with a break between years. (b) Correlation of 5-day average anomalies of 300 mb height with the factor time series in (a).

anomalies. The horizontal structure for this mode, shown in Fig. 3, is very similar to that obtained from the monthly data, shown in Fig. 1. The factor time series, also shown in Fig. 3, indicates that this mode has large amplitude fluctuations on time scales from one to several 5-day periods. For the 5-day average anomalies, this was the only zonally-symmetric mode as the other modes were mainly zonal wavetrains.

Hence, the most important variations of height in the SH on time scales from a week to a season are primarily zonally-symmetric, involving opposing departures of height in middle and high latitudes.

## 3. Variations of the transient eddy statistics

In his comparison of the transient eddy statistics between the winters of 1979 and 1980, Trenberth (1984) showed that the stronger westerly jet at high latitudes in 1979 was associated with a poleward shift of the storm track and that the anomalous convergence of momentum by the transient eddies into the jet would have helped to maintain the anomalous flow. Trenberth (1987) has also shown that momentum flux convergence by the transient eddies is the dominant mechanism maintaining the mean westerly jet in the SH.

Table 1. *Months used for the high-latitude mode composites*

| | |
|---|---|
| MIN composite: | 9/77, 8/78, 7/79, 8/79, 6/80, 8/82, 9/82, 7/83 |
| MAX composite: | 8/77, 7/78, 7/80, 8/80, 9/80, 8/81, 9/81, 9/83 |

To investigate the rôle of transient eddies in the high-latitude mode of low frequency zonal variations in the SH, composites of daily transient eddy statistics have been made for opposite extremes of the mode, using the months given in Table 1. Daily SH analyses from the Australian Bureau of Meteorology were used. The transient eddy statistics were computed for each month using the daily departures from the individual monthly means. No other filtering was used to separate the high frequency and lower frequency transient eddies. These daily SH analyses are less reliable than the monthly mean fields. There are some problems with the transient eddy statistics computed from these analyses. The momentum flux statistics seem to be reliable but the transient eddy heat flux in the upper troposphere is underestimated and may have the incorrect sign (van Loon, 1980; Karoly and Oort, 1987). However, the transient eddy statistics from the Australian analyses were the only ones available for the same period as the mean fields. To reduce the problems with the heat flux, the months chosen for the composites were selected from 6 winter seasons from 1978–83, during which the analysis system and data base were relatively stable. The enhanced data base in the SH during 1979, the year of the Global Weather Experiment, may have had an impact on the transient eddy statistics for that year but the results are similar when this year is excluded from the composites.

The climatological storm track in the SH is more zonally-extensive than in the NH, typically stretching from the south Atlantic Ocean to south of Australia, through about 180° of longitude (Trenberth, 1981, 1982). Even in the Pacific Ocean, there is significant transient eddy activity. As an indicator of the transient eddy activity, the composite mean daily standard deviation of 500 mb height, $\sqrt{(z'^2)}$, for the negative extreme of the high-latitude mode (MIN) is shown in Fig. 4, together with the difference between the composites for the two extremes (MIN–MAX). These differences are comparable with the monthly standard deviation of the transient eddy activity, indicating that the differences of the transient eddy activity between the 8-month composites are significant. There is an overall poleward shift of the storm track and it extends further into the Pacific Ocean. Although the differences have a generally zonal character, there are large local differences of opposite sign. This is similar to the differences between the winters of 1979 and 1980 shown in Fig. 22 of Trenberth (1984).

In the following, we summarize the changes using zonal means of the transient eddy statistics. The composite zonal mean transient eddy statistics for the extreme of the high latitude mode associated with the stronger westerly jet (MIN) are shown in Fig. 5, together with the differences between the composites for the two extremes (MIN–MAX). The differences of the composite zonal mean daily standard deviation of height, $[\sqrt{(z'^2)}]$, show larger transient eddy activity at 55°S, in the region of the stronger jet, and reduced activity in middle latitudes, indicating a poleward shift of the storm track, as in Fig. 4. Similarly, the differences in transient eddy heat flux, $[\overline{v'T'}]$, in the lower troposphere show reduced poleward heat flux in middle latitudes and increased flux at high latitudes, consistent with the poleward shift of the storm track. The differences in the transient eddy momentum flux, $[\overline{v'u'}]$, also show the poleward shift of the storm track, with reduced poleward momentum flux in the subtropics and increased poleward flux in middle latitudes. The anomalous convergence of momentum by the transient eddies is consistent with increased westerly wind near 55°S and reduced westerlies near 30°S.

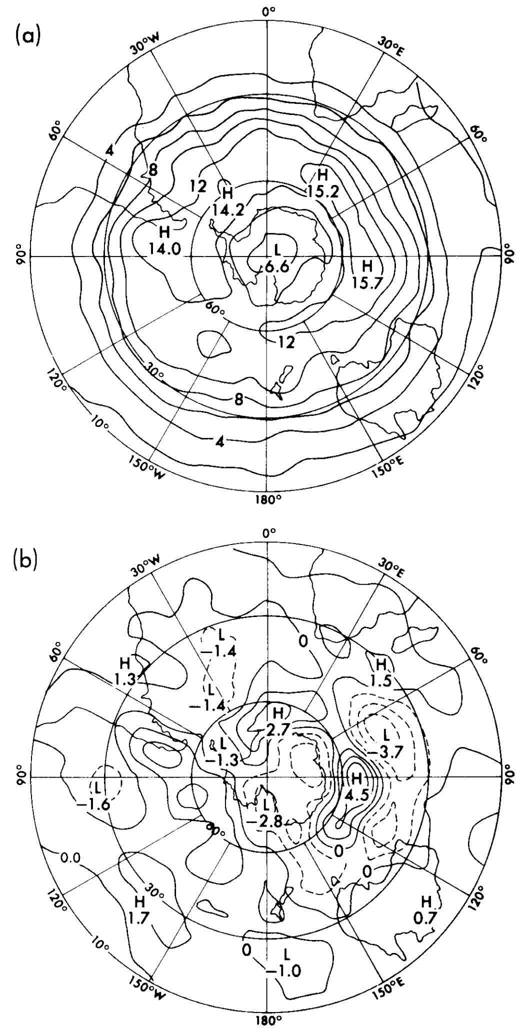


*Fig. 4.* (a) Composite mean daily standard deviation of 500 mb height, $\sqrt{(z'^2)}$, for negative extreme of the high latitude (MIN). (b) Difference of the daily standard deviation of 500 mb height between composites of the high latitude mode (MIN–MAX).

Eliassen–Palm (EP) cross-sections (Edmon et al., 1980) can be used to show the eddy heat and momentum fluxes as the vertical and horizontal components of the EP flux and the effect of the eddies on the mean flow as the divergence of the EP flux. The EP cross-section for the MIN

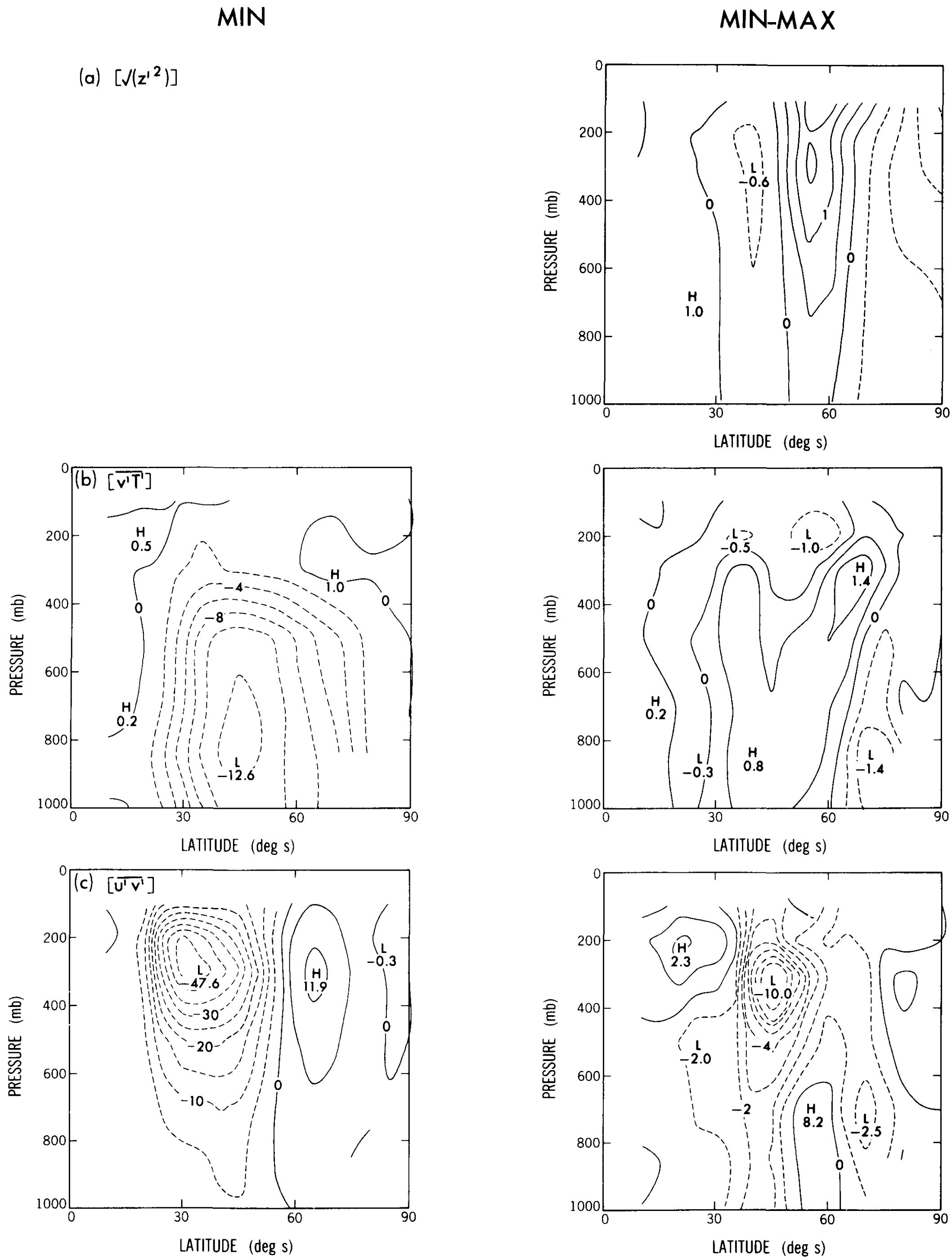


*Fig. 5.* Composite zonal mean transient eddy statistics for the negative extreme of the high latitude mode (MIN, on the left) and difference between composites (MIN–MAX, on the right) for (a) daily standard deviation of height, $[\sqrt{(z'^2)}]$, (dam), (b) heat flux, $[\overline{v'T'}]$, (°C m/s), (c) momentum flux, $[\overline{v'u'}]$, ($m^2/s^2$).

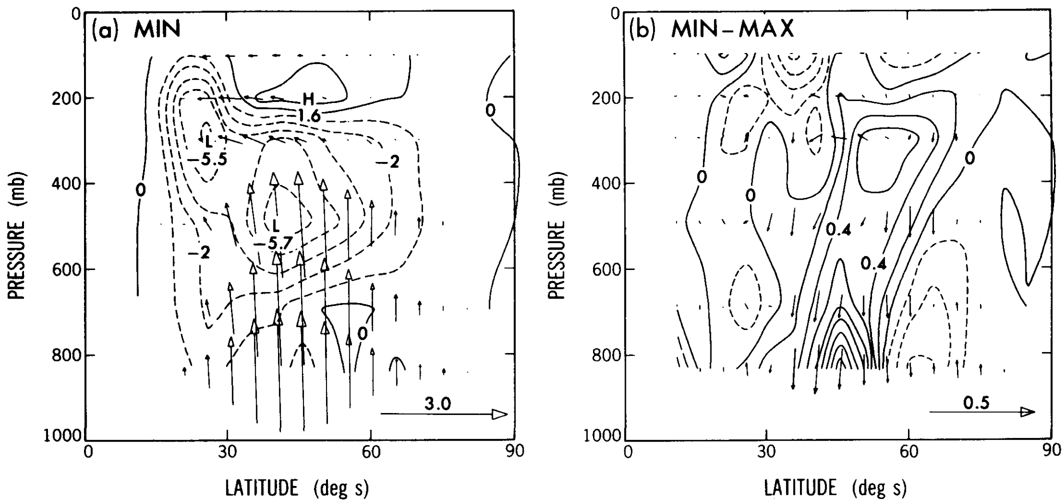


*Fig. 6.* (a) Eliassen–Palm (EP) cross-section for the MIN composite of the high-latitude mode. (b) Difference between the EP cross-sections for composites of the high latitude mode (MIN–MAX).

composite of the high latitude mode and the difference of the EP cross-sections between the two composites are shown in Fig. 6. The anomalous EP fluxes summarize the differences in Fig. 5. The downward arrows at 50°S and upward arrows at 65°S show the changes in the heat flux, while the equatorward arrows in the upper troposphere at middle latitudes show the enhanced poleward momentum flux. The largest differences of the EP flux divergence occur at the lower boundary where they are likely to be balanced by changes in the transformed Eulerian mean meridional flow (Edmon et al., 1980). In the middle troposphere, the largest difference is a region of anomalous EP flux divergence around 55°S, indicating a westerly acceleration of the mean flow by the transient eddies, close to the region of the largest westerly flow differences. There are contributions to this region of EP flux divergence from the momentum flux convergence and the vertical variations of the heat flux in the upper troposphere.

As mentioned earlier, there may be problems with the reliability of some of these transient eddy statistics derived from the Australian daily analyses. Quantities such as the EP flux divergence, which are computed from the gradients of the eddy fluxes, will be sensitive to errors in the flux statistics. Caution must be used when interpreting the details of such fields.

## 4. Discussion

These results show that there are large amplitude variations of the SH circulation in middle and high latitudes which are primarily zonally-symmetric and which occur on time scales from a week to a season. They involve opposing departures of height in middle and high latitudes. In one extreme of this variation, there is an increased height gradient, a stronger westerly jet and more baroclinicity at high latitudes. Associated with these changes in the mean flow, there are changes in the transient eddy activity, including a poleward shift of the storm track. The changes in heat and momentum flux by the transient eddies appear to help to maintain the anomalous mean flow. These results are very similar to those of Trenberth (1984) for the anomalous SH winter circulation during 1979, which was an example of this mode.

Variations of the SH zonal flow have been described by Kidson (1988) in terms of a zonal index cycle, involving low frequency interactions between the zonal flow and the transient eddies. A zonal index cycle driven by the transient eddies might be expected to show a relationship between the eddy forcing and the tendency in the mean flow. The results presented here appear to show a relationship between the eddy forcing and the anomalies of the mean flow, rather than with the tendency of the mean flow.

James and Gray (1986) have analyzed the low frequency variations of the zonal flow and transient eddy activity in a multi-level primitive equation numerical model of the atmosphere. They found that strong horizontal barotropic shear in the zonal flow could inhibit baroclinic instability. Thus the barotropic shears of the zonal wind in middle latitudes shown in Fig. 5d may be important in modulating the transient eddy activity, as well as the variations in the baroclinicity at high latitudes.

The interaction between the intermonthly variations of transient eddy activity and the mean flow described here for the SH are similar to those found in the NH by Lau (1988). He showed that the leading intermonthly variations of transient eddy activity in the Pacific and Atlantic storm tracks are associated with variations of the mean flow near the storm tracks. The changes of the mean flow indicate enhanced baroclinicity in the regions of the anomalous storm tracks and the effect of the eddies is to help maintain the barotropic component of the anomalous mean flow.

This study has been a preliminary analysis of the rôle of transient eddies in low frequency zonal variations of the SH circulation. There are questions about the reliability of the results because of the short period of data used for the analysis and the problems with some of the transient eddy statistics. Further analysis of this interaction using more reliable SH analyses is planned.

## 5. Acknowledgements

I wish to thank Imre Szeredi for making available the results of his Ph.D. research, which stimulated this study. This paper was presented at the Palmen Memorial Symposium in Helsinki in September 1988, and I am grateful to Eero Holopainen and the conference organizers for the financial assistance which allowed me to participate in the symposium. The figures have been prepared by the Scientific Illustration Group at the Geophysical Fluid Dynamics Laboratory, Princeton.

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