Examples of the Horizontal Propagation of Quasi-stationary Waves

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ABSTRACT

Examples of the diagnostic of the horizontal propagation of stationary wave activity proposed by Plumb are presented for a simple model of the atmospheric response to thermal forcing in the tropics, for the observed Southern Hemisphere winter mean stationary waves and for several cases of anomalous quasi-stationary waves in both the Northern and Southern hemispheres. For the simple model, the propagation of wave activity out of the tropics is clear. From the observational data, the apparent sources of anomalous stationary wave activity are located in the regions of the major middle latitude jets and storm tracks in both hemispheres in most cases. The results suggest that midlatitude processes, such as instabilities of the jet stream or interaction with transient eddies, are the major mechanisms for forcing anomalous stationary waves. There are indications that Rossby-like wave propagation from low latitudes plays a role in forcing anomalous stationary waves associated with Southern Oscillation events and with some cases of anomalous stationary waves in the Southern Hemisphere.

1. Introduction

Recently, Plumb (1985) derived a locally applicable (nonzonally averaged) conservation relation for quasi-geostrophic stationary waves on a zonal flow, which was an extension of the Eliassen–Palm relation (Edmon et al. 1980) to three dimensions. The flux which appears in this relation constitutes a diagnostic of the three-dimensional propagation of stationary wave activity. Two examples of this diagnostic were given 1) for a simple model of a barotropic Rossby wavetrain forced by orography and 2) for the observed Northern Hemisphere (NH) winter mean stationary waves. The first example verified the usefulness of the diagnostic, as the results could be compared with an analytic solution. Applications of the diagnostic in the second example suggested that the major sources of the NH winter mean stationary waves are in the region of the Tibetan Plateau and over the western North Atlantic and North Pacific oceans.

This diagnostic of the three-dimensional propagation of stationary waves has been used in modeling studies of anomalous tropospheric stationary waves (Mo et al. 1987) and of stratospheric waves (Marks 1988). In this note, we present examples of the application of this diagnostic to a simple model of a Rossby wavetrain due to thermal forcing in the tropics and to several cases of observed quasi-stationary waves in both the Northern and Southern hemispheres. Our motivation for this study is to clarify the meaning of this diagnostic through the consideration of additional cases as well as to help understand the forcing of observed anomalous stationary waves.

In the examples which follow, we present only the horizontal components of the stationary wave activity flux, rewritten from Eq. (7.1) of Plumb (1985),

$$\begin{aligned} \mathbf{F}_S &= (F_\lambda, F_\phi) \\ &= \sigma \cos\phi \left(\bar{v}^{*2} - \frac{1}{2\Omega a \sin 2\phi} \frac{\partial}{\partial \lambda} (\bar{v}^* \bar{\Phi}^*), \right. \\ &\qquad \left. -\bar{u}^* \bar{v}^* + \frac{1}{2\Omega a \sin 2\phi} \frac{\partial}{\partial \lambda} (\bar{u}^* \bar{\Phi}^*) \right) \qquad (1) \end{aligned}$$

where σ = pressure/1000 hPa, (λ, ϕ) are longitude and latitude, (u, v) are the horizontal geostrophic velocities computed from the geopotential Φ, and Ω and

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a are the Earth's rotation rate and radius, respectively. The overbar indicates the time mean and the asterisk indicates the departure of the variable from its zonal mean. The vector $\mathbf{F}_S$ has been computed in each example from the zonally asymmetric part of the time-mean geopotential and geostrophic winds and mapped onto polar–stereographic coordinates as in Plumb (1985). Horizontal polar–stereographic maps of the geopotential height (Φ/g) and the transformed wave activity flux are shown for each example.

2. Tropical thermal forcing

Plumb (1985) presented the stationary wave activity flux for a simple model of a barotropic Rossby wavetrain forced by orography. That example demonstrated that the wave activity flux defined by (1) was a useful diagnostic of the horizontal propagation of stationary waves. He did not consider the response to thermal forcing. Also, the quasi-geostrophic approximation has been made in deriving the wave activity flux and it may not be a useful diagnostic of Rossby-like wave propagation from the tropics, where this approximation may not be valid.

We have considered the stationary wave response to thermal forcing in the tropics using a steady state primitive equation model linearized about a NH winter flow. The model is a linearized, steady state version of the GFDL spectral GCM (Gordon and Stern 1982; Manabe et al. 1979). It is a sigma coordinate model using nine unevenly spaced levels and spectral truncation at rhomboidal wavenumber 15, as in the GCM. The model has been linearized about a NH winter zonal mean flow which is the long-term mean from a run of the GCM with idealized zonally symmetric boundary conditions and forcing appropriate for January. This mean flow has some minor differences from the observed NH winter mean flow but these are not important for our investigation of the wave activity flux.

The thermal forcing used in the model is a heating given by $Q(\lambda, \phi, \sigma) = A\cos^2[\pi(\lambda - \lambda_0)/8D]\cos^2(\pi(\phi - \phi_0)/2D)\sin[\pi(\sigma - 0.1)/0.9]$, with $A = 10.0$ K day^{-1}, $D = 10°$, $\lambda_0 = 180°$ and $\phi_0 = 5°$. The horizontal structure of the heating is a cosine squared bell in latitude and longitude, centered on 5°N, 180°E and extending over latitudes 5°S to 15°N and longitudes 140° to 220°E. The vertical variation of the heating is sinusoidal in the troposphere, with maximum at $\sigma = 0.55$ and zero heating above $\sigma = 0.1$. The maximum vertically averaged heating is 4.5 K day^{-1} at the center of the forcing. Outside the heating region, there is a zonally uniform cooling such that the zonal mean heating at any latitude is zero. The dissipation in the linearized model includes Rayleigh friction and thermal damping at the lowest three model levels, below $\sigma = 0.8$, to represent boundary layer effects, enhanced Rayleigh friction close to the zero wind line to represent nonlinear effects in the critical layer and the linear biharmonic dissipation used in the GCM.

The steady state solution of the linearized model is obtained using a matrix inversion technique for the specified zonal flow and forcing. The height field solution at 515 and 205 hPa for the tropical thermal forcing is shown in Fig. 1. There is an equivalent barotropic wavetrain of height anomalies extending poleward and eastward from the forcing. The first anticyclonic anomaly, located just poleward of the heating, has large phase variations in the vertical. This solution is similar to the steady model solutions to tropical thermal forcing of Hoskins and Karoly (1981) and Gill (1980). The wave activity flux in Fig. 1 shows wave propagation poleward and eastward away from the forcing region. The wave activity flux has been calculated using geostrophic winds from the height anomalies and is shown poleward of 10°N. If the total wind from the model is used, the wave activity flux is larger but noisier, with less clear pattern of poleward propagation. This suggests that the ageostrophic wind should not be used in the wave activity flux, consistent with its quasi-geostrophic derivation. The poleward propagation of wave activity away from the forcing region is clearer in the upper troposphere. The source of wave activity at 515 hPa appears to be poleward of the actual forcing region. Overall, the wave activity flux appears to be a useful diagnostic of stationary wave propagation, even in this case of thermal forcing in the tropics.

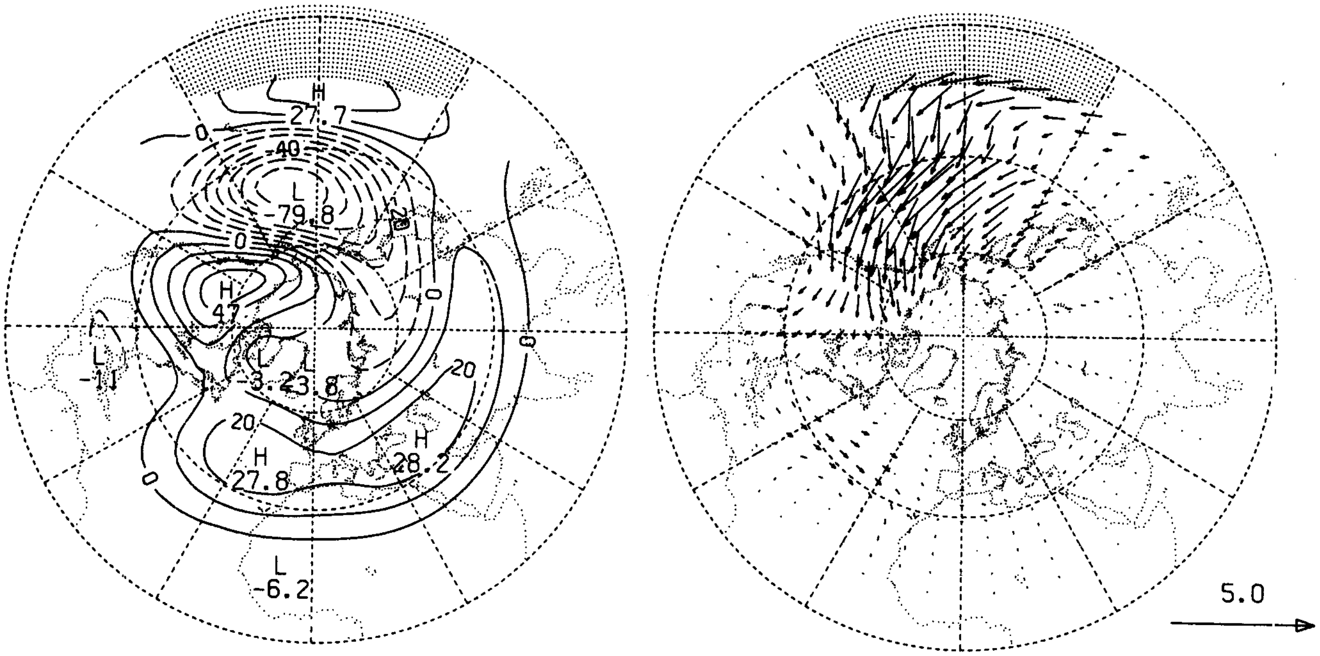
3. Southern Hemisphere winter climatology

The 10-year mean winter (June, July and August) height from the Southern Hemisphere dataset described by Le Marshall et al. (1985) has been used. This dataset was prepared from ten years of daily numerical analyses for the period September 1972 to August 1982 from the Australian Bureau of Meteorology. Some of the properties of the mean stationary waves from this dataset have been described by Karoly (1985a).

The zonal departures of the 300 hPa height in the SH winter are shown in Fig. 2, together with the horizontal component of the stationary wave activity flux defined in (1). The height field is dominated by zonal wavenumber one asymmetries. The wave activity flux shows a major source of stationary wave activity at this level over the Indian Ocean, with zonal propagation towards and south of Australia and equatorward propagation between 150°W and 180°. This source region is located close to the SH winter midlatitude jet and the major SH storm track. There are regions of large but probably spurious flux at 70°W and at 140°W at low latitudes, where the geostrophic wind and the height analyses are unreliable. There are regions of weaker poleward flux in the subtropics over South America and Africa, which may indicate forcing from the tropics. The weak flux source regions at high latitudes, near 20°E and 180°, may indicate forcing from high latitudes associated with Antarctica.

The horizontal pattern of the wave activity flux is the same at other levels in the middle and upper tro-

(a) 515hPa



(b) 205hPa

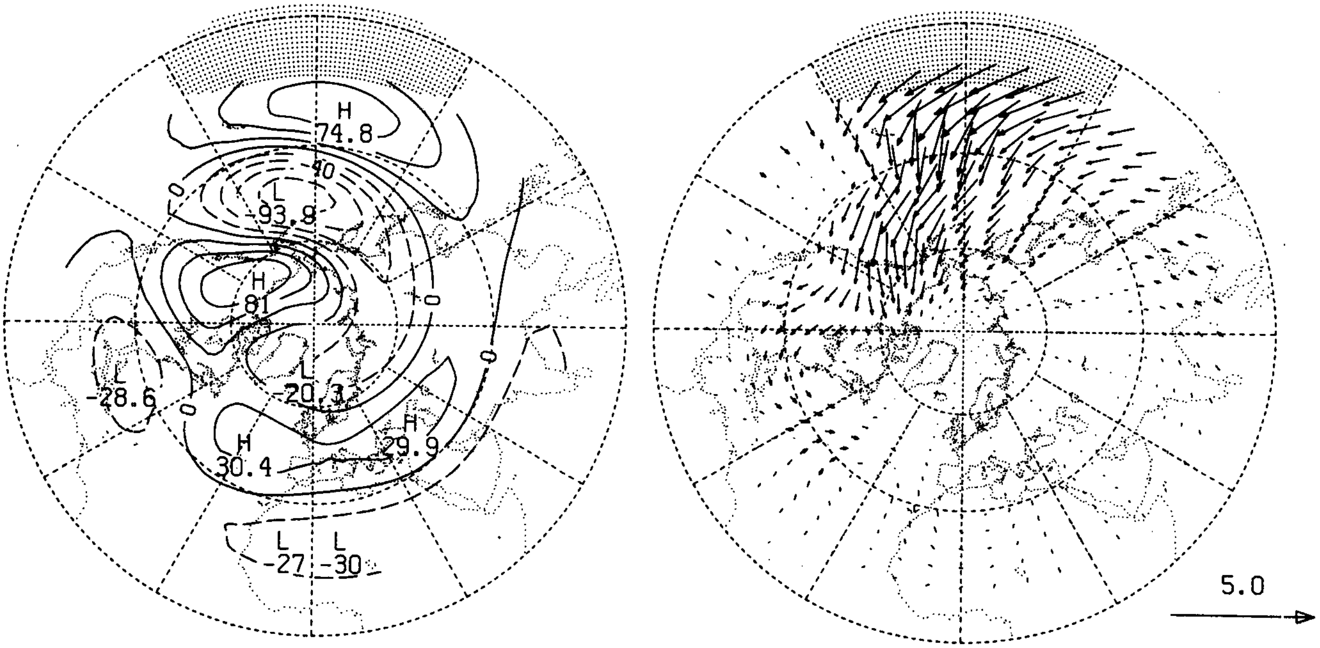


FIG. 1. Steady-state, primitive equation model solution to thermal forcing in the tropics. On the left is the height field (in m) and on the right is the associated horizontal stationary wave activity flux, $\mathbf{F}_S$ (in $\mathrm{m}^2\ \mathrm{s}^{-2}$), with scale shown bottom right, at (a) 515 hPa and (b) 205 hPa. The region with vertical averaged heating greater than 0.5 K day^{-1} is stippled. Lines of latitude and longitude are drawn at 30° intervals and negative contours are dashed.

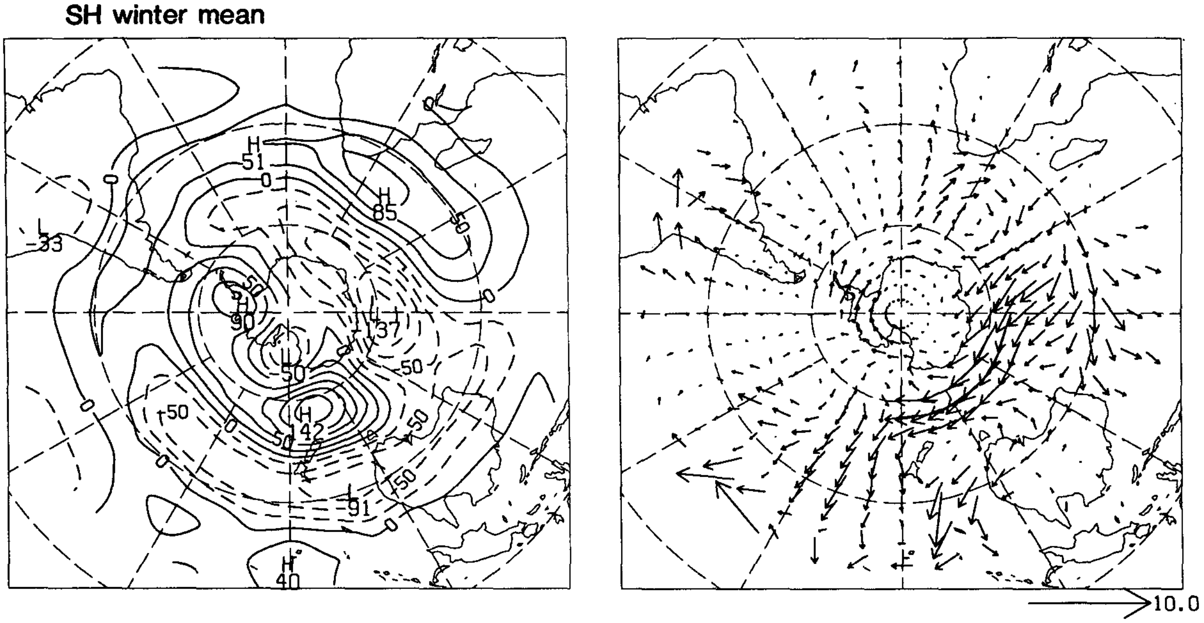


FIG. 2. Time-mean zonal asymmetries of the 300 hPa height field (in m) for the Southern Hemisphere winter (on the left) and the associated horizontal wave activity flux (in $m^2 s^{-2}$), with scale shown bottom right (on the right).

posphere as the waves have an equivalent barotropic structure. They have small phase tilt with height and small meridional heat flux so the vertical component of the stationary wave activity flux is small and probably unreliable.

In the NH winter climatology presented by Plumb (1985), it was possible to associate the pattern of stationary wave activity flux with the major features in the height field. For the SH, it is more difficult to find such an association between the flux in the Indian and Southern oceans and the wavenumber one anomalies in the height field.

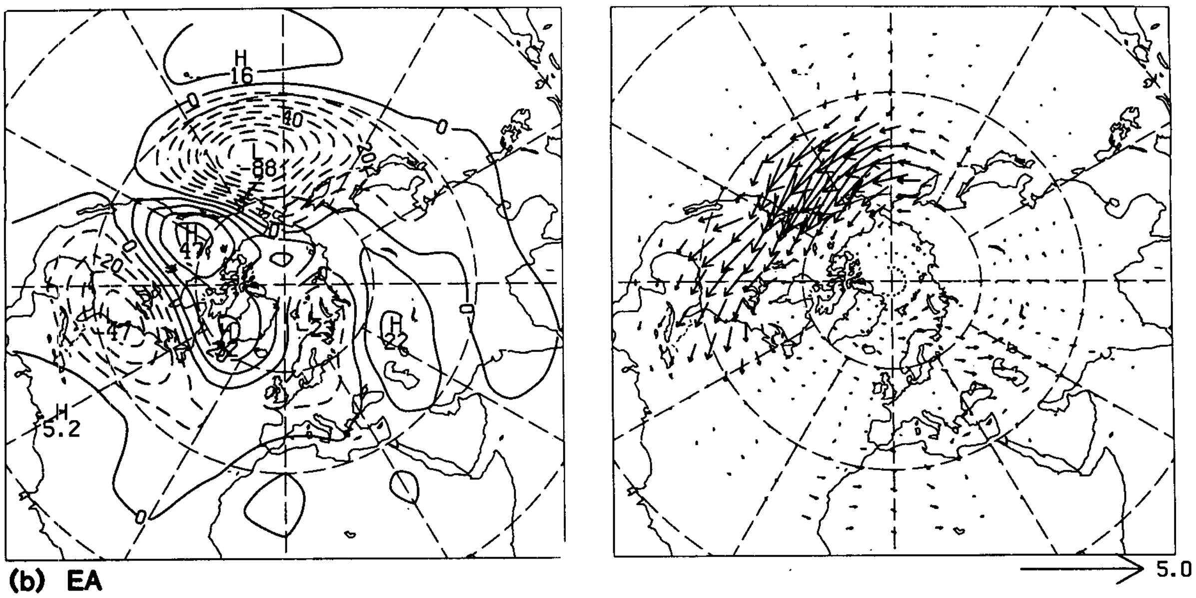
The location of the major stationary wave activity source in the SH close to the midlatitude jet and storm track suggests that the forcing mechanism may be associated with local processes such as instabilities of the jet or with transient eddies, either eddy transports or latent heat release within the storms, rather than orographic or large-scale thermal forcing. We had expected to find a stronger indication of tropical forcing of stationary waves in the SH than in the NH, particularly from the Indonesian region, but this is not apparent. It should be noted that the stationary wave activity flux is a quasi-geostrophic diagnostic and some caution should be used in its interpretation in low latitudes.

4. Northern Hemisphere anomalous stationary waves

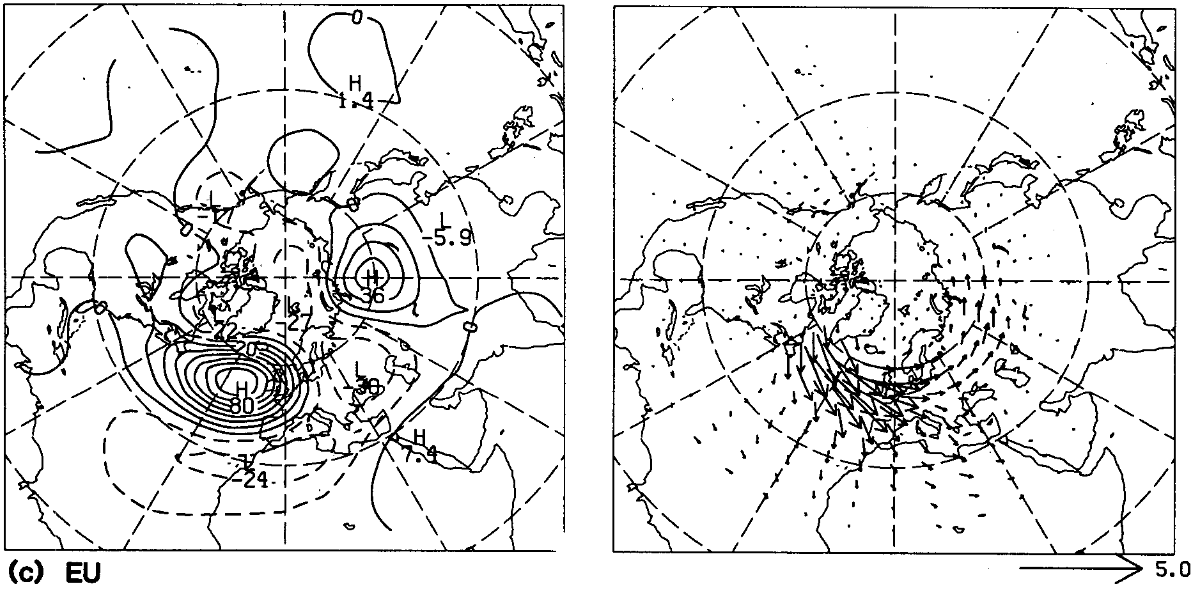
Wallace and Gutzler (1981) have described several teleconnection patterns in the NH monthly height field. These patterns were identified using correlation and composite analysis of 15 years of monthly mean NH winter height analyses. The patterns are associated with anomalous quasi-stationary waves in different regions of the NH. Height anomalies at the 500 hPa level associated with these teleconnection patterns have been computed by Nakamura et al. (1987) using linear regression of the midwinter mean height against the pattern indices defined by Wallace and Gutzler (1981). The data used by Nakamura were 2-month (January and February) mean fields from the U.S. National Meteorological Center analyses for the 35-year period 1946–80. Here, we have calculated the wave activity flux for the anomalous stationary waves directly from the zonally asymmetric part of these regression height anomalies of Nakamura et al. (1987). The significance of computing the wave activity flux directly from the height *anomalies* rather than from the total height field is discussed in the Appendix. The height anomalies and wave activity flux are shown in Fig. 3 for the Pacific–North American (PNA), East Atlantic (EA) and Eurasian (EU) patterns.

The height anomalies in the PNA pattern show a wavetrain from the Pacific Ocean extending east and then south over North America. There is zonally directed wave activity flux with source over the North Pacific Ocean and equatorward flux over North America. The source of the flux in the region of the Pacific jet and storm track would appear to agree with the instability theory for the PNA pattern (Frederiksen 1983; Simmons et al. 1983) or, perhaps, with forcing by transient eddies in the Pacific storm track. There is some evidence of weak poleward flux in the subtropics near 160°W, suggesting that Rossby-like wave propagation from low latitudes may play a minor role in forcing the PNA pattern (Hoskins and Karoly 1981).

(a) PNA



(b) EA



(c) EU

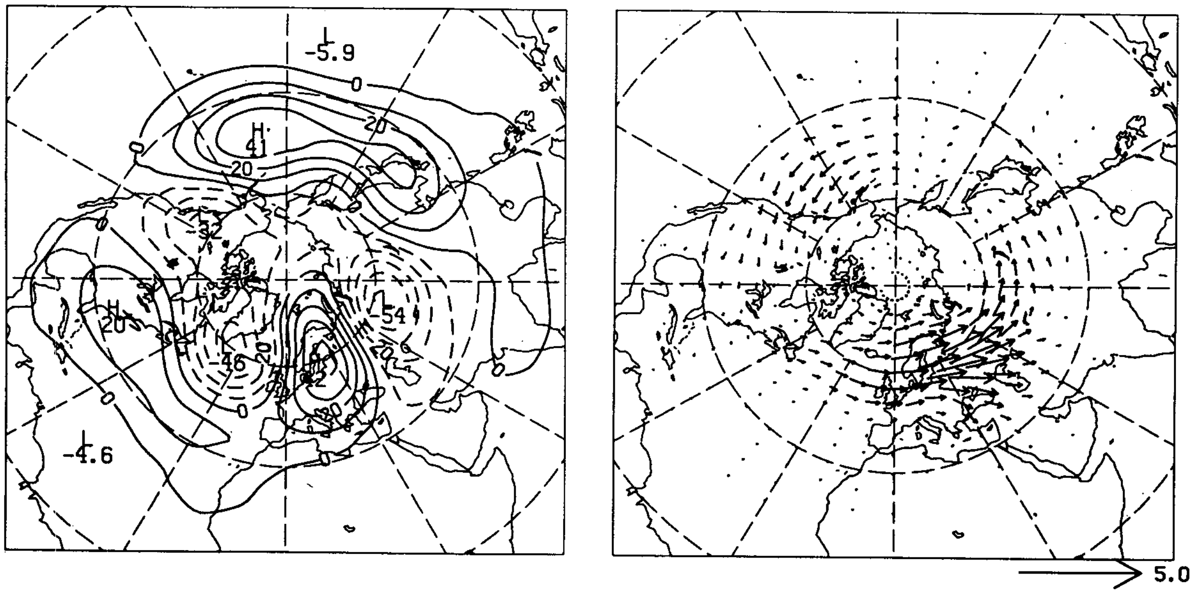


FIG. 3. Northern Hemisphere winter regression anomalies of 500 hPa height (on the left) and associated horizontal wave activity flux (on the right) for (a) Pacific–North American (PNA) pattern, (b) East Atlantic (EA) pattern and (c) Eurasian (EU) pattern.

The location of the major stationary wave activity source for the PNA pattern is not consistent with tropical forcing of the PNA pattern and Rossby-like wave propagation from low latitudes. However, it is possible that the effect of tropical forcing could be transmitted to middle latitudes by a local Hadley circulation and that the effective stationary wave source would be some distance from the forcing (Sardeshmukh and Hoskins 1985).

The East Atlantic and Eurasian patterns are associated with height anomalies and zonally oriented wave activity flux over the east Atlantic Ocean and Europe in the first case and over Europe and Asia in the second case. The apparent source for the Eurasian pattern is mostly to the east of that for the East Atlantic pattern. In both cases, there appears to be a splitting of the flux into two branches, one with zonal propagation at high latitudes and the other with more equatorward propagation.

In all three cases, the wave activity flux has largest amplitude in middle and high latitudes and is primarily in the zonal direction, with more equatorward components at the eastern end of the wavetrains. The direction of the wave flux generally agrees well with steady Rossby-like wave propagation on the sphere (Hoskins and Karoly 1981).

For all these cases, height anomalies at 500 hPa have been used as this level was used by Nakamura et al. (1987). The results presented in section 2 for the model response to thermal forcing in the tropics show clearer propagation of wave activity out of the tropics in the upper troposphere. Hence, the regression analysis of Nakamura et al. (1987) has been repeated using January–February mean 300 hPa height analyses from NMC for a shorter 18-year period, 1964–81. These data were available poleward of 20°N and were not extrapolated to the equator, unlike Nakamura et al. (1987). Data for a longer period or at 200 hPa were not available. The PNA pattern is the only case for which there is a noticeable difference in the wave activity flux between 500 and 300 hPa. For the PNA pattern at 300 hPa, there is larger wave activity flux from the tropics into midlatitudes around 160°W, as shown in Fig. 4. In the upper troposphere, there is more evidence of tropical forcing in the Pacific region playing a role in the PNA pattern, but the major source of wave activity at 300 hPa is still over the North Pacific Ocean.

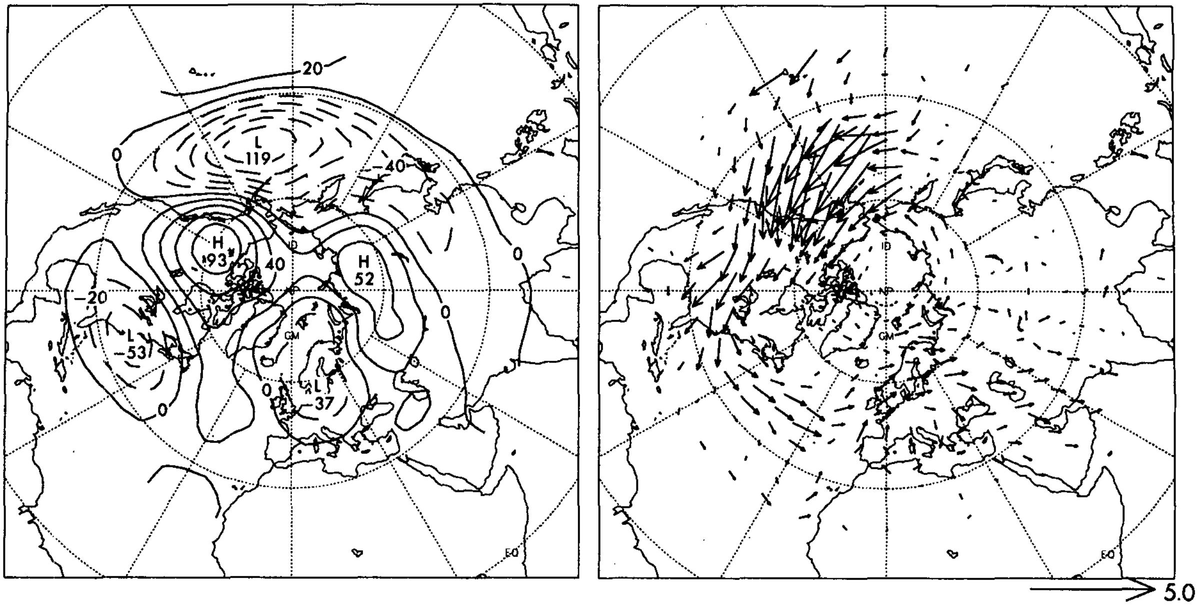
To contrast the height anomalies for the PNA pattern with those associated with El Niño–Southern Oscillation (ENSO) events, the regression analysis was repeated using several Southern Oscillation indices. For all these ENSO regression height anomalies, there was more evidence of propagation of wave activity from the tropics than for the PNA pattern. One example is shown in Fig. 4, for which the index was the April to March (12 month) mean of the difference of normalized monthly pressure anomalies between Tahiti and Darwin (a common Southern Oscillation index). There is strong propagation of wave activity out of the tropics over the central Pacific and a weak source of wave activity over the North Pacific. The differences in wave activity flux between the PNA pattern and the ENSO pattern are dependent on small changes in the height field over the subtropical Pacific, with a larger southwest to northeast height gradient at 30°N, 150°W in the ENSO case. They do not depend on the large zonal mean anomalies in the ENSO height pattern. It should be noted that these differences occur in a region where the analyses are not very reliable. Similar differences between height anomalies for the PNA pattern and ENSO events have been described by Wallace and Jiang (1987).

5. Southern Hemisphere anomalous stationary waves

Mo and White (1985) have carried out a similar study of the variations of the SH winter monthly mean height field to that of Wallace and Gutzler (1981). They were able to identify a zonal wavenumber three pattern in middle to high latitudes and several regional patterns indicating contrasts between continents and oceans. Their analysis was carried out using only 9 years of data. A more comprehensive analysis of the SH monthly mean height has recently been completed by Szeredi (1987) using rotated factor analysis of 15 years of analyses for the period 1972–87 from the Australian Bureau of Meteorology. Szeredi was able to identify a meridional wavetrain pattern in the SH winter as well as the wavenumber three pattern of Mo and White (1985). Composite winter height anomalies at 300 hPa for these two patterns were prepared by Szeredi (1987) using the 10 months with the largest values of the indices for these patterns. They are shown in Fig. 5, together with the composite winter 300 hPa height anomalies for the ENSO event years of 1972, 1976/77 and 1982 from Karoly (1985b). The wave activity flux has been computed for these three examples of anomalous SH quasi-stationary waves in the same way as in the previous section.

The wavenumber three pattern height anomalies have large amplitude between about 30°S and 70°S and are associated with large zonal wave activity flux around the whole hemisphere. There is some indication of focusing of the flux into the region over the Drake Passage, south of South America and equatorward propagation over Australia. For the meridional wavetrain pattern, there appears to be a source of wave activity in the subtropics near eastern Australia, with poleward flux over New Zealand to the high latitude South Pacific and equatorward propagation from high latitudes over South America. Szeredi (1987) has shown that this pattern is associated with fluctuations of cloudiness in the region of the South Pacific convergence zone. The source of wave activity flux is in the region of the winter subtropical jet over Australia and instability of this jet may be involved in the meridional wavetrain.

(a) PNA PATTERN



(b) ENSO PATTERN

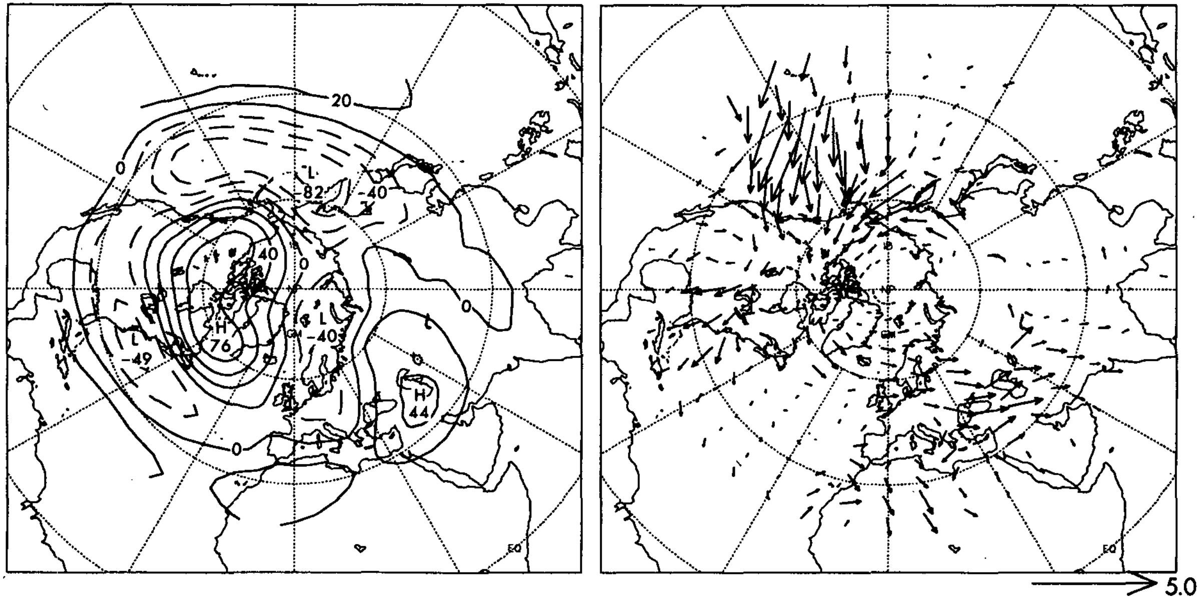
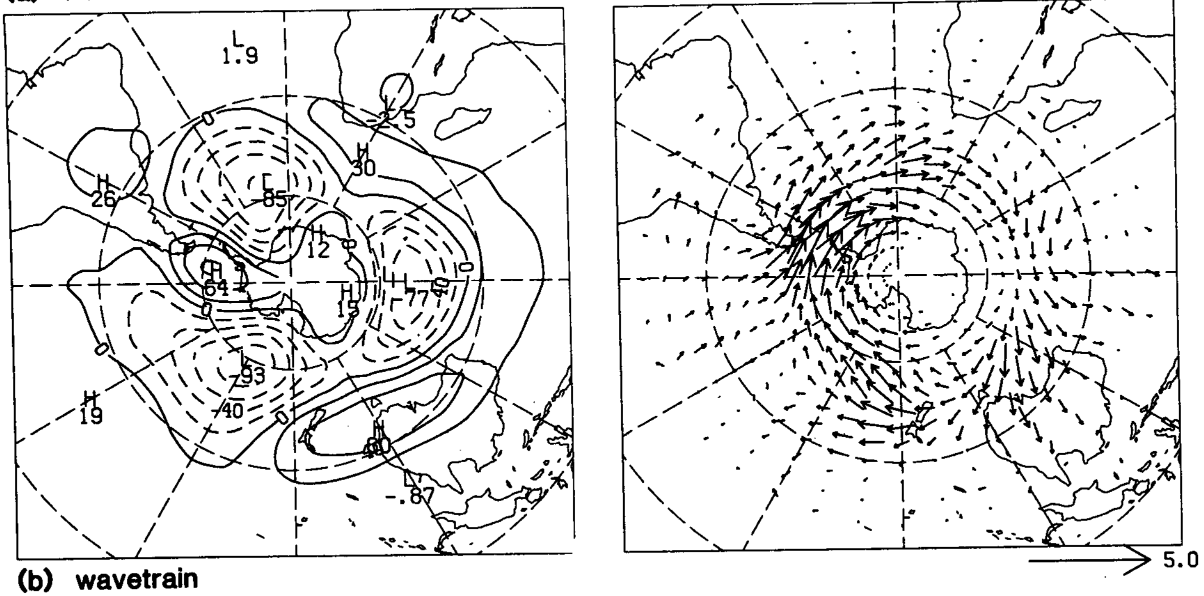


FIG. 4. As in Fig. 3, but at the 300 hPa level for (a) PNA pattern and (b) ENSO pattern.

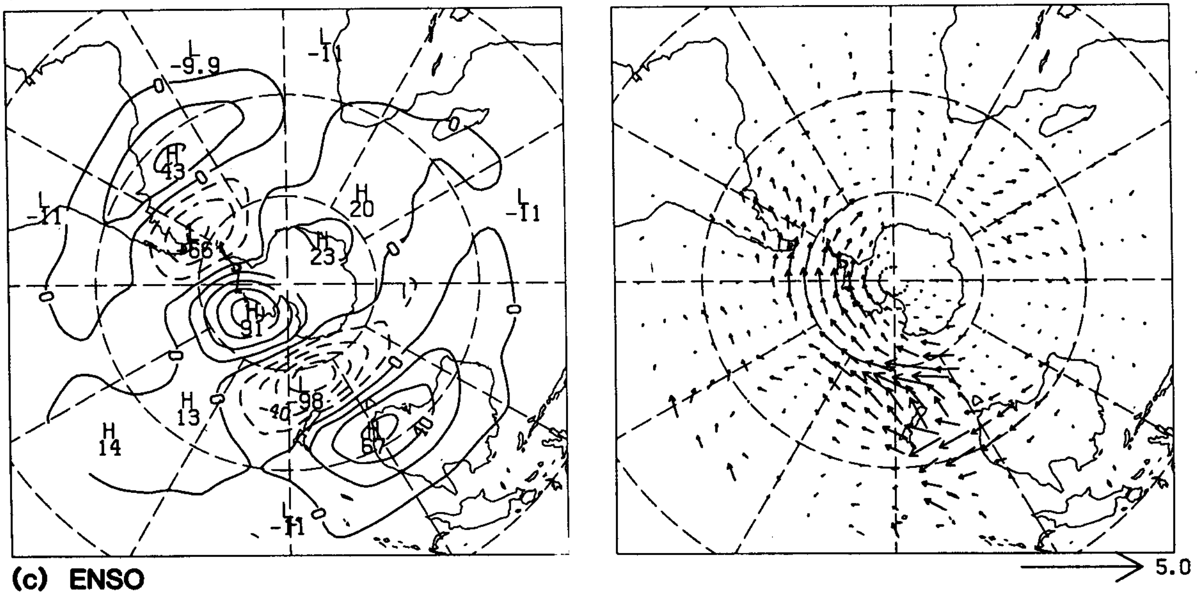
The final example was chosen to be representative of the SH response to anomalous low latitude forcing associated with ENSO events. The largest wave activity flux appears over the subtropical Pacific Ocean. There are indications of weak poleward flux over the eastern Pacific and larger zonal flux over high latitude South America and the South Atlantic Ocean. The wavetrain pattern of height anomalies and flux vectors is less clear in this ENSO example than in the previous case. If the ENSO anomalies are associated with the simple shift of a tropically forced wavetrain, a dipole wave source would be expected, associated with anomalous heating east of the date line and cooling over Indonesia. There is some indication of this in Fig. 5c, with the two regions of largest wave activity over Australia and east of the date line.

There is negligible correlation between time series of the meridional wavetrain pattern and the Southern Oscillation Index; or between the height anomalies in Figs. 5b and 5c, indicating that these are two distinct patterns. Both these final two examples suggest that Rossby-like wave propagation from the tropics may be

(a) wavenumber 3



(b) wavetrain



(c) ENSO

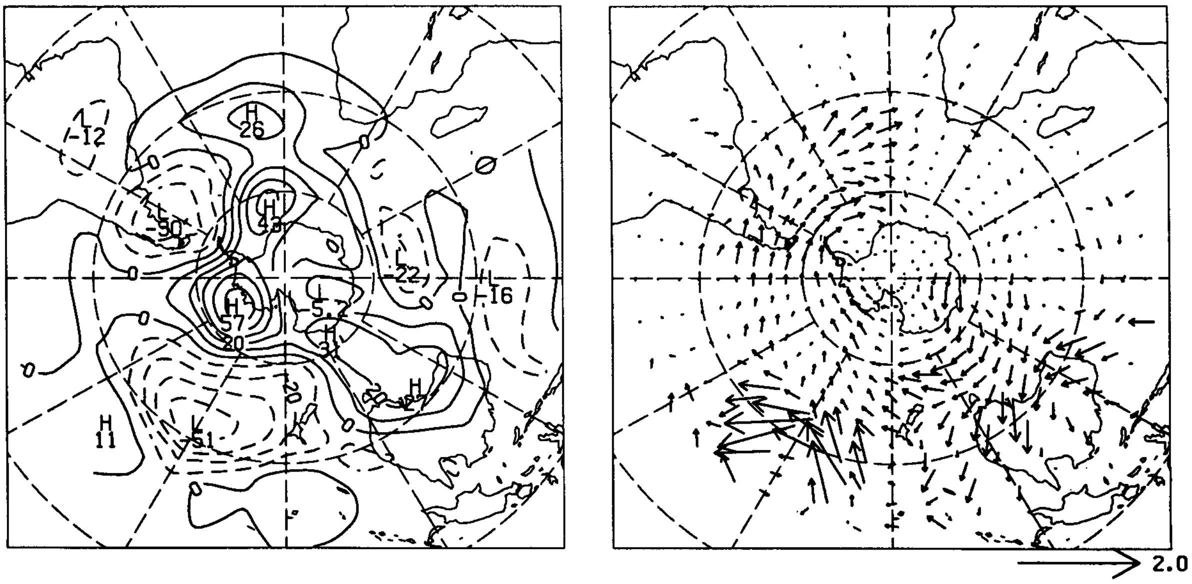


FIG. 5. Composite Southern Hemisphere winter anomalies of 300 hPa height (on the left) and associated horizontal wave activity flux (on the right) for (a) zonal wavenumber three pattern, (b) meridional wavetrain pattern and (c) ENSO pattern (note the different contour interval and arrow scale in this case).

an important mechanism for forcing anomalous quasi-stationary waves in the SH. However, the link between the low latitude and high latitude regions of large wave flux in Fig. 5c is weak.

6. Discussion

These examples have confirmed that the horizontal stationary wave activity flux defined by Plumb (1985) is a useful diagnostic of the horizontal propagation of quasi-stationary waves. The propagation of wave activity out of the tropics is clear in the simple model response to tropical thermal forcing. In some of the observational cases, the magnitude and direction of the flux is not immediately apparent from the height field. This suggests that caution should be used in determining the direction of wave propagation from visual inspection of the height anomalies alone.

The propagation of stationary waves in the Northern Hemisphere climatology studied by Plumb (1985) showed little if any indication of wave propagation away from tropical forcing. It is possible, however, that wave activity propagation from low latitudes is being masked by the effects of midlatitudes—e.g., the phase structure of a response to an Indonesian source could be disrupted by a wavetrain downstream of the Tibetan Plateau and thus not be obvious in the flux pattern. The results presented here for a Southern Hemisphere climatology make this possibility seem unlikely. Unless there are some subtle interhemispheric asymmetries in the characteristics of stationary wave propagation, one would anticipate that the response to stationary tropical forcing in the two winter hemispheres would be comparable. If, in northern winter, the effects of tropical forcing were sufficiently large to make a significant contribution to the stationary wave field then such effects should completely dominate the weaker climatological waves of southern winter, and therefore be more readily identified. On the basis of our results for southern winter, in which we find no strong evidence of propagation from low latitudes, we therefore conclude not only that tropical forcing is not a major factor in the Southern Hemisphere wintertime stationary wave climatology but also that its importance must be even weaker in northern winter.

For the Northern Hemisphere anomaly cases, large stationary wave activity fluxes occur in middle latitudes in the jet stream and storm track regions with little indication of propagation from low latitudes except during ENSO events. This suggests that midlatitude processes, such as instabilities of the jet streams or interaction with transient eddies, may be important forcing mechanisms for anomalous stationary waves in the Northern Hemisphere. This is also true for the Southern Hemisphere cases but, in the Southern Hemisphere, there is more indication of wave activity flux from low latitudes.

The comparison of the PNA and ENSO cases has shown that small changes in the height anomalies at low latitudes can lead to marked changes in the derived wave activity fluxes. Since these height anomalies are in regions of relatively sparse observations, they are less reliable in these regions and there must be some doubts about the reliability of the wave activity fluxes.

Acknowledgments. We wish to thank Mike Wallace for providing the Northern Hemisphere regression height anomalies of Nakamura et al. (1987) and the Australian Bureau of Meteorology for allowing access to their Southern Hemisphere analyses. This note has been greatly improved by the comments of Glen White and another reviewer who suggested the inclusion of the simple model response to thermal forcing, and Isaac Held who suggested the comparison of the wave activity fluxes for the PNA and ENSO patterns. These model calculations and the processing of the 300 hPa height data were carried out at the Geophysical Fluid Dynamics Laboratory, Princeton while D.J.K. was a visitor with the Atmospheric and Oceanic Sciences Program, Princeton University. M.T. is supported in the Atmospheric and Oceanic Sciences Program at Princeton University by NOAA Grant NA87EAD00039. We are grateful to Leon Rotstayn for assisting with the computations and Alison Leicester for typing the manuscript. Part of this study was supported by a grant from the Australian Research Grants Scheme.

APPENDIX

Stationary Wave Flux Anomalies

The stationary wave flux is defined in (1) in terms of the stationary wave velocities ($\bar{u}^*$, $\bar{v}^*$) and geopotential $\bar{\Phi}^*$. If we now replace "stationary" with "quasi-stationary" (i.e., we consider the entire slowly varying component of the wave field, rather than just the long-term climatology), then we may expand

$$\begin{pmatrix}\bar{u}^*\\ \bar{v}^*\\ \bar{\Phi}^*\end{pmatrix}(\lambda, \phi, z, t) = \sum_n \gamma_n(t)\begin{pmatrix}u_n\\ v_n\\ \Phi_n\end{pmatrix}(\lambda, \phi, z)$$

where $\gamma_n(t)$ is a time-varying index of the nth component of the total field. One component is the long-term climatology, $\gamma_1 = 1$.

If now we assume that the components of the above expansion are mutually orthogonal in time over the interval $[t_1, t_2]$ (this is always true for patterns determined by principal component analysis) so that

$$\int_{t_1}^{t_2} \gamma_m(t)\gamma_n(t)dt = \delta_{mn}$$

then, e.g., it follows that

$$\bar{u}^*\bar{v}^* = \sum_m \sum_n \gamma_m(t)\gamma_n(t)u_m(\lambda, \phi, z)v_n(\lambda, \phi, z).$$

Hence the time average flux $\bar{\mathbf{F}}$ may be written as the sum over all components:

$$\bar{\mathbf{F}} = \sum_n \mathbf{F}_n,$$

where $\mathbf{F}_n$ is the flux associated with the nth component, calculated by simply replacing $(\bar{u}^*, \bar{v}^*, \bar{\Phi}^*)$ in (1) by (u_n, v_n, Φ_n). Thus the anomalous fluxes (the contribution to the total, long-term average flux, by the anomalies) may in this sense be equated with the fluxes associated with the anomalous fields.

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