Rossby Wave Propagation and Teleconnection Patterns in the Austral Winter

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(Manuscript received 14 February 1994, in final form 21 February 1995)

ABSTRACT

Observational evidence of and theoretical support for the Northern and Southern Hemisphere teleconnection patterns in the austral (Southern Hemisphere) winter are examined through an upper troposphere streamfunction teleconnectivity map and time-lag cross-correlation analysis using ECMWF initialized analysis 200-hPa winds for the 11 June–August periods from 1979 to 1989.

As was previously found for the Northern Hemisphere winter, the regions of strong teleconnectivity, particularly in the winter hemisphere, tend to be oriented in the zonal direction and coincide with the location of the major jet streams. Although equatorward propagation from the Northern and Southern Hemispheres is observed, little evidence of cross-equatorial propagation has been found.

For comparison, the response of a barotropic model, linearized about a climatological 300-hPa June–August time-mean flow to localized forcing is determined. It is found that the activity tends to be trapped inside each of the Southern Hemisphere subtropical and polar jet streams, with these acting as waveguides. In the Northern Hemisphere a weak waveguide belt is found near 40°N around the whole hemisphere. The patterns simulated by the model are generally in good agreement with the teleconnectivity study described above. Both the observations and the model support the existence of the Pacific–South American pattern.

1. Introduction

Teleconnection analyses give a global view of the organized, wavelike result of local anomalies in atmospheric circulation and their influence on the circulation in remote regions. The pioneering study of Wallace and Gutzler (1981) used 500-hPa geopotential monthly mean data to produce teleconnection patterns for the Northern Hemisphere (NH) in winter. To better understand these results, Blackmon et al. (1984a) partitioned atmospheric fluctuations with periods of a few days or longer into two categories: those in the 2.5–6.0-day period range (short timescale), which were isolated by means of a bandpass filter, and those with periods of 10 days or longer, which were isolated with a low-pass filter. They found that the former distur-

bances exhibited variance and covariance patterns characterized by elongated maxima suggestive of storm tracks and an association with baroclinic waves, while the latter disturbances (intermediate and longer timescales) were viewed as representing a collection of different phenomena. Those associated with intermediate timescales (period between 10 and 30 days) were characterized by wavelike structures and the successive downstream development of new centers of action, with each center remaining almost stationary, and are usually interpreted as Rossby wave energy dispersion on a sphere (Blackmon et al. 1984b).

Compared to the Northern Hemisphere, studies on teleconnections in the Southern Hemisphere are relatively few in number, for example, Mo and White (1985) and Kidson (1988). More recently, Kousky and Bell (1992) have produced an atlas of Southern Hemisphere teleconnection patterns for the winter (May–September) and summer (November–March) seasons, using monthly mean 500-hPa geopotential height anomalies. Berbery et al. (1992) have also studied the existence of Southern Hemisphere teleconnections for both seasons (December–February and June–August), offering both observational and numerical evidence.

There have been many observational studies of the global circulation and low-frequency variability for the

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Northern and Southern Hemispheres (e.g., Blackmon 1976; Wallace and Blackmon 1983; Schubert 1986; and Trenberth 1979, 1980, 1981a,b, 1986; Kidson 1991; respectively). Discussions of high-frequency variability can be found for example in Wallace et al. (1988) for the Northern Hemisphere and Trenberth (1981b, 1991) for the Southern Hemisphere. The intermediate frequency (10–30-day period) and low-frequency (>30-day period) variability, particularly the former, have not often been addressed in the literature. Blackmon et al. (1984a) presented some observational results for the Northern Hemisphere for the winter season, and more recently Hsu and Lin (1992) have performed a similar study for the entire globe for the December–February season.

The dominant form of evolution on intermediate timescales is through the dispersion of energy through stationary wave trains, as evidenced by the development of new centers downstream and the decay of old centers upstream. This is clearly distinct from the phase propagation associated with the high-frequency transients (baroclinic waves).

A qualitative explanation of the wave train nature of the teleconnection patterns observed by Wallace and Gutzler (1981) was provided by Hoskins and Karoly (1981) based on the theory of stationary Rossby wave dispersion on the sphere. Using December–February mean 300-hPa data as a background flow in a barotropic model, Hoskins and Ambrizzi (1993, hereafter referred to as HA) have simulated most of the patterns documented by Hsu and Lin (1992) and Berbery et al. (1992). For stationary forcing, HA showed that the local wave pattern was formed within a few days, that the remote wave pattern was formed in about two weeks, and that the wave patterns, once set up, persisted with little qualitative change. Thus if there is variability on the timescale of 10–30 days in the source region, it is consistent that related variability would be observed along the predicted Rossby wave path.

The objective of the present investigation is to give similar observational and numerical evidence of the Northern and Southern Hemisphere teleconnection patterns that exhibit Rossby wavelike characteristics in the June–July–August (JJA) season. Through a teleconnectivity map and time-lag cross-correlation analysis in the manner of Hsu and Lin (1992), the teleconnection patterns will be documented in sections 2 and 3, respectively. A theoretical and barotropic modeling analysis similar to that given in HA will be presented in sections 4 and 5. Section 6 contains a summary of the main results and some concluding comments.

2. Teleconnectivity

The European Centre for Medium-Range Weather Forecasts (ECMWF) initialized data at 1200 UTC averaged for the 11 June–August periods from 1979 to 1989 are used in this study. The basic data are 200-hPa

winds on a 5° by 5° grid. Streamfunctions were computed from vorticity by inverting the Laplacian operator in spherical harmonic space having first interpolated the winds onto a Gaussian grid. As in the northern winters reported by Hsu and Lin (1992), a zonally symmetric pattern also exists in the Austral winter which usually tends to mask the wavelike structure of teleconnection patterns. Consequently, zonal means were subtracted. The eddy streamfunction field was processed through a 10–30-day bandpass Butterworth tangent filter, as in Hsu and Lin (1992). This procedure is designed to isolate the signals on intermediate timescales, based on the definition of Blackmon et al. (1984).

In order to reveal the underlying teleconnection structure in the streamfunction field of intermediate timescales, a teleconnectivity map as defined by Wallace and Gutzler (1981) was computed. The map in Fig. 1 is based on 2088 one-point correlation maps for base points every 5° in both longitude and latitude between 70°N and 70°S. Each arrow is directed toward the point where the variation of streamfunction on intermediate timescales shows the largest negative correlation with the base point. As in the December–January–February (DJF) season, the regions of strongest teleconnection in the NH are found near the Asian and Atlantic jet streams and are oriented almost in the zonal direction. The location of maximum correlation in JJA is farther north than in DJF (Hsu and Lin 1992), and the correlations are weaker. This is consistent with the observation of the more poleward location and weaker and less organized transient eddy activity in the northern summer in the NH. In the Southern Hemisphere the geographic dependence is still evident but not as strong as in the Northern Hemisphere. However six regions of maximum correlation can be seen: 1) Australia; 2) subtropical South Pacific; 3) South America; 4) extratropical Atlantic and Indian Ocean, and polar regions near 60°S; 5) between 120°E and 180°; and 6) between 80°W and 30°W. Like those in the Northern Hemisphere,

FIG. 1. Teleconnectivity of 10–30-day bandpass-filtered eddy streamfunction at 200 hPa. The values have been multiplied by 100; values smaller than 40 are not contoured, and the contour interval is 5. Locations of maximum teleconnectivity are indicated by the arrows.

sphere, the regions of strong teleconnectivity tend to be oriented in the zonal direction and coincide with the location of jet streams. One region of cross-equatorial teleconnectivity, which is oriented in the meridional direction, can be seen in the tropical Atlantic.

3. Temporal evolution

The structure and time evolution of teleconnection patterns have been further investigated by examining time-lag cross correlations between the points of maximum correlation in Fig. 1 and all grid points. Only eight of them will be shown here for the sake of brevity. Degrees of freedom for every correlation in maps shown here were computed in the same way as in Hsu and Lin (1992). The results indicate that degrees of freedom are all well above 100. By assuming 60 degrees of freedom, correlations have to be above 0.3 and 0.25 to reject the null hypothesis of no correlation at the 0.01 and 0.025 significance levels, respectively. In the following maps, only those points with absolute values greater than 0.2 are plotted.

a. Southern Hemisphere

Figure 2 shows the lag correlation maps for the base point (30°S , 120°W) at 3-day intervals. The day -3 map (Fig. 2a) exhibits a wavelike structure west of the base point along 30°S . Its zonal scale is equivalent to about zonal wavenumber 6. By day 0 (Fig. 2b), new cells have developed northeast of the base point, while the cells to the west have weakened. The downstream development has a strong suggestion of equatorward propagation. In the day $+3$ map (Fig. 2c), another wavelike structure crossing the southern tip of the South American continent is seen, while the equatorward branch described above appears to have weakened. During the successive downstream development of new cells, individual centers of maximum correlation also move eastward by about 20° of longitude in 6 days, an average speed of about 3 m s^{-1} .

Lag correlation maps for the base point (35°S , 45°W) are given in Fig. 3. At day -3 , a wavelike structure emanates southeastward from the subtropical southern Pacific, crosses the southern tip of South America, and bends northeastward into the Atlantic Ocean. Equatorward propagation along the eastern side of the South American continent and in the Southern Atlantic is the dominant feature at day 0 (Fig. 3b). By day $+3$, the appearance of new cells in the Indian Ocean near 50°S and west of Australia suggests a different behavior.

Presented in Fig. 4 are lag correlation maps for the base point (25°S , 40°E). At day -3 , the dominant pattern is a wavelike structure spreading from the Antarctic Peninsula northeastward into the South Atlantic and southern Africa. The day 0 and day $+3$ fields show a new wavelike pattern developing eastward across the

FIG. 2. Lag correlation between the streamfunction at (30°S , 120°W) and streamfunction at every point (a) 3 days earlier, (b) day 0, and (c) 3 days later. The values have been multiplied by 100; values between -20 and 20 are not contoured. Negative values are dashed, and the contour interval is 10. The location of the base point, (30°S , 120°W), is marked by a cross sign.

Indian Ocean in the band 10° – 30°S , crossing Australia by day $+3$. A similar pattern can also be found between 30° and 60°S as shown in Fig. 5 for the base point (45°S , 110°E), through the day ± 3 figures do not give such a clear picture of eastward development of the pattern. Equatorward propagation is suggested over Australia at day 0 and southern Africa at day $+3$. The zonal scale of the 10° – 30°S pattern (Fig. 4) is predominantly that of zonal wavenumber 5–6, while it is about zonal wavenumber 4 for the 30° – 60°S pattern (Fig. 5). Patterns of zonal wavenumber 3 scale are dominant in the higher latitudes for the base point (60°S , 175°W), as shown in Fig. 6. The evolution of the pattern is suggestive of successive downstream development. In ad-

FIG. 3. Same as in Figs. 2a–c but for base point (35°S, 45°W).

dition the day +3 picture indicates a possible propagation from the southern Pacific into the tropical eastern Pacific.

b. Northern Hemisphere

Lag correlation maps for three base points are shown in this section to illustrate the characteristics of the patterns in the Northern Hemisphere corresponding to the maximum correlations shown in Fig. 1. In the Eurasian region, the patterns tend to evolve downstream near the core of the jet stream for the base point (35°N, 75°E), as shown in Fig. 7. Unlike the Southern Hemisphere developments, a westward movement of the positive correlation region from Indochina to the Arabian Peninsula is also observed. Figure 8 shows lag correlation maps for the North Pacific base point (40°N, 170°W). Two arclike wave patterns are seen. At day -3, one emanates northeastward from south of Japan following

an arclike route into the tropical eastern Pacific. The second wavelike structure is seen at day +3 from the central Northern Pacific into the North American continent. A similar evolution is also found in the North America and Atlantic region for the base point (40°N, 55°W), as shown in Fig. 9.

c. Summary

Based on the lag correlation maps for many base points in the vicinity of teleconnectivity maxima, the upper tropospheric routes along which teleconnection patterns appear to develop can be determined. They are shown schematically in Fig. 10 and can be identified in the one-point correlation maps shown here. As found by HA for DJF, the jet streams are favored locations for such propagation routes. In particular the subtropical route in the Southern Hemisphere coincides with the subtropical jet that passes over Australia.

FIG. 4. Same as in Figs. 2a–c but for base point (25°S, 40°E).

FIG. 5. Same as in Figs. 2a–c but for base point (45°S, 110°E).

Lag correlation statistics have been calculated for base points every 10° of longitude and latitude between 20°N and 20°S to investigate the strength of the equatorward propagation. Such equatorward propagation is found mostly in the Southern Hemisphere in the Indian Ocean, western Pacific, and South America. Little evidence of cross-equatorial propagation has been found. The cross-equatorial teleconnection in the Atlantic shown in Fig. 1 is a dipole straddling the equator that moves slowly westward and does not exhibit wavelike structure. Westward drift is a common characteristic for the teleconnection patterns within 20°N and 20°S. Hsu and Lin (1992) found that such cross-equatorial propagation occurs only in DJF in the regions of equatorial westerlies. During JJA, easterlies prevail around the globe in the tropical upper troposphere, and so the present results are consistent with their findings. The two studies show that upper tropospheric extratropical–

tropical interaction is stronger in the winter hemisphere.

As in the Hsu and Lin (1992), the orientation of each cell in the teleconnection pattern exhibited here tends to be perpendicular to the route along which successive downstream development of new cells occur. Hsu and Lin loc. cit. interpreted the patterns as evidence of Rossby wave dispersion, and the same interpretation would seem applicable here. Hoskins and Ambrizzi gave a theoretical and modeling discussion of this hypothesis for DJF, and a similar investigation for JJA will now be presented.

4. Basic state, theory, and the barotropic model

It was shown in HA that many of the observations and model results for DJF could be qualitatively understood in terms of Rossby wave propagation. The theoretical basis is discussed in HA, and only a brief

FIG. 6. Same as in Figs. 2a–c but for base point (60°S, 175°W).

FIG. 7. Same as in Figs. 2a–c but for base point (35°N, 75°E).

review is given here. The basic parameter in the theory is the stationary Rossby wavenumber $K_s = (\beta_*/\bar{U})^{1/2}$, where β_* is the poleward gradient of absolute vorticity and $\bar{U}$ is the westerly wind. Figure 2 of HA showed schematic K_s profiles and ray path refraction for different situations, with waves being refracted toward higher values of K_s and being reflected from a turning latitude. At a critical latitude at which the zonal wind is zero and K_s becomes infinite, rays are refracted toward the meridional direction with their meridional scale and group velocity tending to zero. A region with a maximum in K_s equal to K_2 flanked by minimum values K_1 provides a waveguide for zonal wavenumbers K_1 to K_2 (see Fig. 2c from HA). This situation is particularly likely to occur in a strong westerly jet in which the curvature of the flow tends to give a larger relative maximum in β_* than in $\bar{U}$. Consequently, strong westerly jets can act as Rossby waveguides. It was sug-

gested in HA that this theory could be applied to a longitudinally varying flow using the local values of $\bar{U}$, β_* , and K_s .

As in HA and many previous barotropic studies, a 300-hPa basic flow is used here. Equivalent barotropic, midlatitude structures are probably best represented using the flow from a slightly lower level (Held et al. 1985). However, Hoskins and Karoly (1981) and further integrations using a baroclinic model, to be presented elsewhere, indicate that the upper troposphere is the most important region for Rossby wave propagation in the tropical and subtropical regions. The 300-hPa level is then a compromise between these two choices. Comparison can also be made with the observed equivalent barotropic structures shown by their 200-hPa signatures discussed in section 3.

The basic flow used in this paper is a 6-year 1979–85 JJA time-mean 300-hPa rotational flow derived

FIG. 8. Same as in Figs. 2a–c but for base point (40°N, 170°W).

FIG. 9. Same as in Figs. 2a–c but for base point (40°N, 55°W).

from ECMWF analyses. Some aspects of the flow are shown in Fig. 11. For the sake of comparison between the two solstitial seasons, the structure of this picture is similar to Fig. 3 in HA.

The Asian and North American zonal wind maxima (Fig. 11a) are weaker and farther north than in DJF. Their separation is less marked and they could be considered to compose a single westerly maximum spiraling poleward from the tropical North Atlantic, through Asia, North America, and the northern North Atlantic. One important characteristic of the Southern Hemisphere winter is the presence of a double jet. The subtropical jet has its maximum of 48 m s^{-1} located east of Australia near 20°S, 160°E. The polar jet has a maximum of 36 m s^{-1} near 45°S, 40°E. The presence of easterlies around the entire tropical belt suggests that there are no favorable regions for cross-equatorial propagation (Webster and Holton 1982).

The Mercator coordinate meridional gradient of the absolute vorticity β_m [defined by Eq. (2.12) in HA] is shown in Fig. 11b. It exhibits maxima in the jets with minima to the north and south. For the strong subtropical Southern Hemisphere jet, these minima are negative, and it resembles the Asian jet in the Northern Hemisphere winter.

Figure 11c gives the geographical distribution of K_s [as defined by Eq. (2.13) in HA] for β_m and $\bar{U}$ positive. The zero wind line $\bar{U} = 0$ is shown by the thickened contour, and the zero β_m and K_s (but positive $\bar{U}$) line by dots. It should be noted that each jet region contains quite uniform values of K_s , bounded meridionally by lower values. Thus the theory predicts that they may act as waveguides. There are clear similarities between the K_s distribution and the teleconnectivity shown in Fig. 1, and this supports the application of the simple theory.

In summary, the main features we can deduce from Figs. 11a–c that can be compared with the numerical results to be shown below are the following:

- 1) Subtropical and polar waveguides in the Southern Hemisphere. The former extending nearly 20°S from Madagascar to 45° east of the date line and having typical stationary wavenumber 7, and the latter from south of Africa at about 50°S to the tip of South America near 60°S and having typical stationary wavenumber 4.
- 2) A waveguide along the Asian jet from North Africa to the eastern North Pacific, with typical stationary wavenumber 7–8.
- 3) A weak waveguide along the North Atlantic jet from the western North Atlantic to northern Europe, with typical stationary wavenumber 6–7.
- 4) There are no favorable regions for cross-equatorial propagation.

Numerical integrations of a barotropic model designed to compare with the observed patterns and test the existence of such features will be described in the

FIG. 10. Schematic plot of teleconnection propagation routes deduced from numerous lag correlation maps for the base points from 70°N to 70°S for every 10° of latitude and longitude.

FIG. 11. The climatological JJA 300-hPa flow based on ECMWF data for the period 1979–85. (a) Westerly component of the wind U ; contour interval is 6 m s^{-1} . (b) Mercator coordinate meridional gradient of the absolute vorticity β_m [defined by Eq. (2.12) in HA]; contour interval is $1 \times 10^{-11} \text{ s}^{-1} \text{ m}^{-1}$. (c) Stationary wavenumber K , [defined by Eq. (2.13) in HA] for β_m and $\bar{U}$ positive; contours for wavenumbers 0, 4, 5, 6, 7, 8, 10, and 15, and also 25–30, producing a thickened contour indicating singular values of K . The position of this thickened contour differs slightly from that of the $\bar{U} = 0$ contour in (a) mainly because of differences obtained by interpolating very differently behaved quantities on a finite grid. In all panels, negative contours are dashed, and zero contours are dotted. Lines of latitude and longitude are drawn every 30° .

next section. As in HA, this model is based on the non-divergent barotropic vorticity equation and is solved using the spectral transform technique with a triangular truncation at wavenumber 21. The basic flow discussed above is maintained by a constant forcing.

The local source of Rossby wave is specified as fD , where f is the Coriolis parameter and the divergence D , in general, has a cosine squared amplitude in an ellipse with a semiaxis 45° in longitude and 22.5° in latitude or a circle of diameter 30° . The actual structure of the perturbation forcing for various solutions discussed in section 5 is similar to those given in Fig. 4 of HA. The divergence D is usually multiplied by 10^{-6} so that the calculation is effectively linear, but the re-

sults are scaled so that the maximum value of D is equal to $3.0 \times 10^{-6} \text{ s}^{-1}$.

5. Barotropic model results

a. Subtropical and polar jets

In an attempt to verify if the jet waveguide behavior found for studies of the Northern Hemisphere in winter occurs also for the Southern Hemisphere winter jets, circular forcings were placed at $(20^\circ\text{S}, 40^\circ\text{E})$ and $(45^\circ\text{S}, 30^\circ\text{E})$ at the entrance of the subtropical and polar jets. The relative vorticity perturbations for day 12 are depicted in Fig. 12. Figure 12a shows that Rossby wave activity does indeed propagate along the Australian jet stream. The signal moves at about 48 m s^{-1} and produces quasi-stationary features with alternate signs in vorticity and a zonal wavelength of about 70° of longitude. A similar wavelike structure was seen in Fig. 4c. A weak wave train propagates along the polar jet with a zonal wavelength of about 120° of longitude.

A fine contour interval shows that the subtropical wave propagates into the equatorial east Pacific, near the west coast of South America, while the midlatitude wave shows no signs of equatorward propagation and reaches the tip of South America, with an average speed of about 27 m s^{-1} .

FIG. 12. The model vorticity anomaly for the forcing centered at (a) $(20^\circ\text{S}, 40^\circ\text{E})$ and (b) $(45^\circ\text{S}, 30^\circ\text{E})$ at day 12. The contour interval is $5 \times 10^{-6} \text{ s}^{-1}$; negative values are dashed, and the zero contour is not shown. The black circle indicates the forcing position.

FIG. 13. The model vorticity anomaly at day 12 for the forcing at $(50^{\circ}\text{S}, 50^{\circ}\text{W})$. Contour conventions as in Fig. 12.

In contrast, in Fig. 12b the amplitude of the wave propagating inside the polar waveguide is stronger than that in Fig. 12a, and a weaker wave train is found in the subtropical jet. A similar polar wave train was shown in Fig. 5c. The wavelengths and wave activity speeds are similar to those found in the previous case.

There is a marked similarity between the patterns shown in Fig. 12 and those exhibited in the winter Northern Hemisphere in Fig. 5 of HA. The “Austrian” wave pattern is comparable to the Asian wave pattern, even with regard to the curvature toward the equator in the east Pacific. The polar pattern is a stronger version of the Eurasian pattern.

The numerical results presented in Fig. 12 show good agreement with those exhibited in Berbery et al. (1992, Figs. 4c and 5c), in both wave propagation path and zonal wavelength. The implied zonal wavenumber 3–4 in the polar wave train has also been found in many data studies, for example, Trenberth (1980), Mo and Ghil (1987), Farrara et al. (1989), Kidson (1988, 1991). However, the wavelike propagation in the subtropical region observed in the lag correlation maps (Fig. 4) and modeled here (Fig. 12a) with zonal wavenumber 5–6 seems not to have been discussed previously. The agreement is also good with the K_s field (Fig. 11c), which predicts a total wavenumber 7–8 for the same region.

b. South Atlantic

The data analysis study by Berbery et al. (1992) and the analysis presented in section 3, particularly Figs. 2 and 3 (see also the schematic picture Fig. 10), have shown that wave trains coming from the tip of South America can follow, at least, 3 paths: (a) toward the equator, skirting the northeast coast of Brazil; (b) toward the southern African continent; and (c) propagate more zonally, being trapped inside the polar waveguide. For a forcing placed at $(50^{\circ}\text{S}, 50^{\circ}\text{W})$ the K_s field suggests that (b) should be preferred, and this is confirmed in Fig. 13. Study of the temporal evolution up to day 12 shows the propagation of a wave train over

the southern African continent and of weaker ones in the subtropical and polar jets.

c. East and southeast Pacific

Putting an elliptical divergence at $(0^{\circ}, 90^{\circ}\text{W})$ produces a south and southeasterly propagating wave train that crosses South America and reaches the South Atlantic Ocean. By day 12 (Fig. 14a), there is an indication of wave splitting just east of the South American coast, with one wave train propagating toward the equator and the other having a more zonal propagation and eventually reaching the polar waveguide. A wave propagation route similar to this latter one has been suggested by Gao and Stanford (1988), from analysis of 4 years of satellite-derived microwave brightness temperatures (see their Fig. 2c).

For a forcing in the southeastern equatorial Pacific $(30^{\circ}\text{S}, 120^{\circ}\text{W})$, the wave follows an arclike route to the equatorial Atlantic with a turning point near 45°S (Fig. 14b). Due to the similarity of this wave pattern with the Pacific–North America pattern (Wallace and Gutzler 1981), it was named the Pacific–South America pattern or PSA by Mo and Ghil (1987), who found a similar pattern in their data analysis. Figures 2c and 3a from the present study also show this pattern.

In Fig. 14a, the wave propagation into the Northern Hemisphere is relatively weak. Lau and Peng (1992)

FIG. 14. The model vorticity anomaly for the forcing centered at (a) $(0^{\circ}, 90^{\circ}\text{W})$ and (b) $(30^{\circ}\text{S}, 120^{\circ}\text{W})$ at day 12. Contour conventions as in Fig. 12.

FIG. 15. The model vorticity anomaly for the forcing centered at $(40^{\circ}\text{N}, 75^{\circ}\text{W})$ at (a) day 4 and (b) day 12. Contour conventions as in Fig. 12.

have shown through sensitivity tests to the meridional location of the heat source in the east Pacific that the response in the Northern Hemisphere is weak when the forcing is located equatorward of 14°N , which is the case here. Using a fine contour interval, it is seen that the propagation path in Fig. 14a splits in the North Atlantic, with one wave being trapped inside the North Atlantic waveguide and the other propagating inside the Asian waveguide as expected from the K_e picture (Fig. 11c). The next two experiments to be described show these wave patterns more clearly.

d. North Atlantic jet

With circular forcing at $(40^{\circ}\text{N}, 75^{\circ}\text{W})$ near the North Atlantic jet stream maximum, the role of this jet as a waveguide is quite clear at day 4 (Fig. 15a). There is also a perturbation in the entrance to the North African–Asian westerly maximum. By day 12 (Fig. 15b), the wave train inside the North Atlantic waveguide shows no signs of further downstream propagation, instead, it appears to turn equatorward, toward the Arabian Gulf region, although it is not clear if the wave activity is better associated with propagation along the North African westerly maximum. This pattern can also be seen in some experiments of HA and it resembles a pattern found by Blackmon et al. (1984) in their studies for the Northern Hemisphere in winter. Some

wave activity is guided by the Asian waveguide, reaches the central Pacific, and then propagates toward the equator parallel to the west coast of North America. Consistent with the presence of easterlies around the equatorial belt, there is no indication of cross-equatorial wave propagation and no suggestion of organized wave activity in the Southern Hemisphere. The zonal wave-number inside the North Atlantic waveguide is about 6, consistent with a total wavenumber of 6–7 seen in the K_e picture (Fig. 11c). Figure 9c showed in the observations a wave propagation inside the North Atlantic jet, and suggested the turn equatorward toward the Arabian sea, but gave no indication of downstream propagation inside the Asian waveguide. However, the downstream propagation shown in Fig. 7 does clearly demonstrate the effect of the Asian waveguide.

e. North African–Asian jet

To study the waveguide nature of the North African–Asian jet, circular divergence forcing has been placed near the west end of the jet, at $(40^{\circ}\text{N}, 30^{\circ}\text{E})$. As shown by the day 12 solution (Fig. 16), Rossby wave activity does propagate along the Asian jet. Comparing with the DJF picture, Fig. 5 of HA, the Asian waveguide is weaker, shifted northward, and it extends almost up to the west coast of North America. Here, there is an indication of the wave splitting, with one wave going toward the equator, skirting the west coast of Central America, and the other propagating into the North Atlantic waveguide. The zonal wavenumber inside the Asian waveguide is about 7.

The lag correlation analyses shown in Figs. 7 and 8 clearly suggest the wave propagation pattern described above. Experiments with forcing at different points in the Northern Hemisphere midlatitudes (not shown) give similar patterns, suggesting that although the Asian waveguide is weaker during the summer season it has a much longer zonal extension than during the winter season. It therefore tends to dominate the guiding of Northern Hemisphere wave activity.

There are indications in both Figs. 16 and 15b that the propagation path splits near the date line, with a

FIG. 16. The model vorticity anomaly at day 12 for the forcing at $(40^{\circ}\text{N}, 30^{\circ}\text{E})$. Contour conventions as in Fig. 12.

weak train of waves propagating toward the equator. This propagation does not agree with the K_s picture. It appears that wave activity is able to tunnel through the negative K_s region of $\bar{U}$ and β_* maxima extending eastward from the date line near 15°N (Fig. 11). However, lag correlation analyses around this region have not shown such a pattern in the observations.

6. Conclusions

Figure 17 is a summary of all the results of the linear barotropic experiments performed using the JJA 300-hPa flow. As in HA, the background contours are some of the key ones from the basic flow K_s figure (Fig. 11c). The four waveguides, the North African–Asian jet, the North Atlantic jet–North European region, the Southern Hemisphere subtropical (Australian) jet, and the polar jet, are shown by arrows with cross-hatched shafts. The preferred propagation toward and away from these waveguides are indicated by single-shafted arrows. There is no evidence of wave propagation between hemispheres, which is to be expected because the equatorial region is generally dominated by easterly winds.

Comparison between Fig. 17 and Fig. 10, the schematic summaries of the theoretical and observational results, shows them to be very similar. The double waveguide in the Southern Hemisphere is well defined in both. Enhanced meridional propagation in the equatorial east Pacific and Atlantic Oceans, and the propagation over the southern African continent are seen in both pictures. Although it is not expected from the K_s picture (Fig. 11c), there is a suggestion in Fig. 12b of wave propagation from the polar waveguide toward the Australian continent with subsequent trapping inside the subtropical waveguide. Such a pattern has been observed by Berbery et al. (1992) and is seen in our lag correlation analysis (Fig. 5). The wave propagation from the polar waveguide toward the equatorial east Pacific shown in Fig. 10 (see also Fig. 6) is indeed found in some experiments with forcings eastward from that shown in Fig. 12b. The three possible routes from the South Atlantic, skirting the northeast of Brazil, through the southern African continent, and toward the polar waveguide are all in good agreement with the results from the lag correlation analyses.

For the Northern Hemisphere the comparison between the data analysis and the numerical results is even better than for the Southern Hemisphere. This is particularly striking because the points chosen for the time-lag cross-correlation analyses were those with maximum correlation computed in the teleconnectivity map (Fig. 1), while the locations of the forcings in the numerical experiments were based on the K_s picture. From the long North African–Asian waveguide there is propagation toward the eastern subtropical Pacific and across North America. The North Atlantic waveguide finishes in Northern Europe, but there is apparent

FIG. 17. A schematic summary of the waveguides, shown by the cross-hatched shafted arrows, and the preferred propagation patterns, indicated by the single-shafted arrows, deduced from the range of experiments. The background contours are those for K_s equal to 0, 4, 5, 6, and 25–30 taken from Fig. 11c.

propagation across the eastern Mediterranean. The extension of the Asian waveguide from North Africa to near the west coast of North America and then into the North Atlantic waveguide gives the impression of a weak waveguide spiraling around the whole earth in association with the westerly wind maximum, and indeed some of the experiments have shown this behavior.

When compared with the DJF pictures shown in HA, the strong subtropical North African–Asian waveguide has moved some 10° poleward and weakened somewhat. The North Atlantic–Eurasian waveguide has shortened so that there is now only a single-latitudinal structure. However the double-waveguide structure is now found to be marked in the Southern Hemisphere, where the single, short, polar waveguide has now been replaced by extended, parallel subtropical and polar waveguides. There is still a tendency for propagation into the equatorial region in the east Pacific and Atlantic but, with the easterlies found there in JJA, it is less marked than in the DJF season of westerlies.

The Southern Hemisphere polar waveguide has been frequently discussed in the literature. Studies of planetary waves in the Southern Hemisphere by Trenberth (1980) and of teleconnections by Mo and White (1985) and others have described the presence near 55°S of a pattern having a zonal scale equivalent to wavenumber 3 or 4. This is confirmed by the K_s picture and numerical results given here. Probably because of the previous lack of suitable datasets, only more recently has the subtropical jet been recognized as a possible waveguide (Berbery et al. 1992). The propagation from the east South Pacific to the equatorial Atlantic following an arclike route found in our data and numerical studies is similar to the PSA (Pacific–South American) pattern discussed by Mo and Ghil (1987). Evidence of wave propagation from the east Pacific to the Indian Ocean has been shown by Gao and Stanford (1988) and is supported by our results.

Because there is such a measure of agreement between the results from the observational analyses and the barotropic theory and modeling in this paper, the

limitations of the theory and modeling are of less concern than would otherwise be the case. On the timescale of interest here, it is not believed that the barotropic results are sensitive to the nature of the forcing required to maintain the basic flow. Results from a recent study using a baroclinic model are generally supportive of those from the barotropic model shown in this paper.

Acknowledgments. We wish to acknowledge the very useful comments made by anonymous reviewers on an early version of this paper. One of us (TA) wishes to acknowledge CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for financial support and IAG-USP (Instituto Astronômico e Geofísico, Universidade de São Paulo) Brazil, which allowed the completion of this research.

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