Traveling Planetary-Scale Waves and Blocking

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ABSTRACT

The possible relation between blocking-type flow patterns in the atmosphere and large-scale traveling waves has been investigated. A 30-yr time series of observational 500-hPa geopotential-height data was used to study the relation between westward-moving planetary-scale waves 1 and 2 and blocked flow. It was found that, depending on longitude, 20%–40% of blocks were related to traveling wave 1, whereas the percentage was smaller for wave 2. The study confirms results of earlier studies that suggest a possible important role for large-scale, westward-moving waves in many blocking episodes.

1. Introduction

It is widely acknowledged that flows similar to those normally referred to as "blocked" can be caused by interaction of synoptic-scale and larger-scale features. This has been discussed in detail by Shutts (1986), who demonstrated that the eddy forcing mechanism, or eddy straining mechanism as Shutts calls it, was of importance in connection with the development of a blocking anticyclone over the North Atlantic in February 1983. Similarly, Mullen (1987) showed the importance of nonlinear effects of synoptic-scale transients on a number of observed blocks and blocks simulated by a general circulation model. In addition, various numerical experiments have verified that synoptic-scale eddies can create blocking-type flow patterns. Results from experiments of this kind have been summarized by Egger et al. (1986). In a series of papers (Kung and Baker 1986; Tanaka and Kung 1988; Kung et al. 1989), E. C. Kung and coworkers analyzed the energetics of major blocking cases. The analyses were done in zonal wavenumber domain, and wavenumbers 1 and 2 were identified to be the scale range to represent winter blocking development with energy input from the synoptic scales.

It is quite clear that we cannot obtain a full understanding of blocks by ignoring the synoptic scale. Nevertheless, it is important to understand the role of large-scale waves. For example, Austin (1980), Arai (1981), Quiroz (1987), and Lejenäs and Döös (1987) have documented a frequent coincidence of large-scale traveling waves and blockings in Northern Hemisphere data. Lindzen et al. (1984) speculated that slowly propagating Rossby waves can contribute to persistent anomalies. In this regard, another possible relevance of large-scale traveling waves to blocking episodes was suggested by Lindzen (1986). Most definitions of blocking involve some measure of persistence. Lindzen points out that, to ensure uniqueness of blocking phenomenon so defined, persistence ought to mean long lasting compared to the time scales for planetary-scale, free Rossby waves. Otherwise, a persistent feature identified as a blocking ridge might simply reflect a slowly moving, free Rossby wave.

Here we present the results of an observational study of only large-scale traveling waves and blocking. They are based on a 30-yr dataset and thereby extend Quiroz's study (he used three years of data) and that of Arai, who concentrated on a subset of cases that included only very large amplitude traveling waves. They also extend the study of Lejenäs and Döös by virtue of the fact that we consider the individual wavenumbers 1 and 2, and examine only westward-propagating waves that are generally considered to be similar to free Rossby waves (Eliasen and Machenhauer 1965, 1969; and many others). We combine methods used to isolate large-scale traveling waves that were used in Madden and Speth (1989) with those used in Lejenäs and Økland (1983) to objectively identify flows associated with

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blocking. Our results relate the frequency and longitudinal distribution of the coincidence of large-scale traveling waves and blocking flows.

2. Data

The source of the data used in this study is the U.S. National Meteorological Center (NMC) historical maps. The data are archived at the National Center for Atmospheric Research in Boulder, Colorado. Thirty years of daily 1200 UTC 500-hPa geopotential-height data from 1 January 1950 through 31 December 1979 were studied. Data from less than 2% of the days are missing either because they were not in the original set or because during our analyses we found that they were obviously erroneous. The available data were first interpolated from the NMC octagon to a 5° × 10° latitude–longitude grid from 20° to 80°N using a 16-point interpolation routine. The data were then Fourier analyzed along each latitude line, and the first 18 zonal wavenumbers were retained. The resulting large-scale geopotential height at some latitude is given by

$$z(\lambda)_{i,j} = [z]_{i,j} + \sum_{m=1}^{18} (a_{m,i,j} \cos m\lambda + b_{m,i,j} \sin m\lambda). \tag{1}$$

Here λ is the longitude and m is the zonal wavenumber. The brackets about the first term on the right represent a zonal mean, and the subscripts signify data from the ith year and jth day.

3. Filtering of the waves and introducing an index to identify blocking

We filtered raw data by subtracting out the smooth annual variation, adopting the method used by Lejenäs and Madden (1982). The smooth annual variations of the spatial cosine and sine coefficients of a given wavenumber m are indicated by $\tilde{a}_{m,\cdot,j}$ and $\tilde{b}_{m,\cdot,j}$. They are approximated by retaining the annual, semiannual, 3 cycles per year, and half of the amplitude of 4 cycles per year, of the Fourier transform of $a_{m,\cdot,j}$ and $b_{m,\cdot,j}$. The $a_{m,\cdot,j}$ and $b_{m,\cdot,j}$ are the averages for the jth day of $a_{m,i,j}$ and $b_{m,i,j}$ over all i years. The filtered coefficients were then given by

$$(a_{m,i,j})_f = a_{m,i,j} - \tilde{a}_{m,\cdot,j} \tag{2a}$$

$$(b_{m,i,j})_f = b_{m,i,j} - \tilde{b}_{m,\cdot,j}, \tag{2b}$$

where m is equal to 1 or 2, depending on the wave to be filtered, and f means filtered. Filtering out the annual variation in this way does not favor any time scale, and spectra computed before and after the filtering are identical at frequencies higher than 5 cycles per year or periods shorter than 73 days (Madden and Speth 1989). The geopotential height at a specific longitude λ of the filtered wave was then obtained as

$$(z_{m,i,j})_f(\lambda) = (a_{m,i,j})_f \cos m\lambda + (b_{m,i,j})_f \sin m\lambda. \tag{3}$$

These data, with the annual variation removed, will be referred to as "filtered data," but we stress that the filter removes only the annual variation. We also stress that filtered data are used only when isolating the traveling wave. All other computations are done with the original data as given by (1).

We focused our study on winter and spring seasons when blockings are most frequent, and consequently, we extracted data for the time period 1 December–31 May for all available 29 years. For this data subset, 40 days were missing, which is considerably smaller than the 2% for the whole dataset (cf. section 2). The geopotential height for the filtered wave was plotted in a time–longitude diagram, and the longitude for the ridge was indicated in the diagram (example for wave 1 in Fig. 2 to follow).

To identify atmospheric blocking, some criteria or index need be used (see, for example, Rex 1950; Dole and Gordon 1983; Lejenäs and Økland 1983). We used the index adopted by Lejenäs and Økland (1983) to study characteristics of blocking. Their index was the 500-hPa geopotential-height difference between 40° and 60°N:

$$I(\lambda)_{i,j} = z(\lambda)_{i,j,40°\mathrm{N}} - z(\lambda)_{i,j,60°\mathrm{N}}, \tag{4}$$

where λ is the longitude and i, j indicate a specific day. Here $z(\lambda)$ means the geopotential height of the unfiltered data, and it is based on all 18 wavenumbers m as in (1). The index was computed at every 10° of longitude. Blocking is defined to occur in a specific region when the index is negative in that region (Lejenäs and Økland 1983).

The criteria used by Rex (1950) and Lejenäs and Økland (1983) to identify blocking situations focus on characteristic features of the 500-hPa flow field during a block. Rex defined the longitudinal position of a block as the longitude of the westerly current split, whereas Lejenäs and Økland used the geopotential-height difference between 40° and 60°N. Thus, statistics obtained using these criteria should give similar results, although the Lejenäs–Økland criterion gives longitudes for the block somewhat east of what Rex's criterion gives. Dole and Gordon (1983) studied persistent positive height anomalies, and since a blocking anticyclone implies positive height anomalies, this criterion has been used frequently to identify blocking situations. Madden and Lejenäs (1989) have shown that flows with small or negative $I(\lambda)_{i,j}$ are in fact associated with persistent 500-hPa heights over the eastern Atlantic and western Europe. There is, however, a difference between the two types of criterion, which presumably explains why Rex and Lejenäs and Økland did not find blockings in northern Russia, where Dole and Gordon found a maximum in occurrence of persistent positive anomalies.

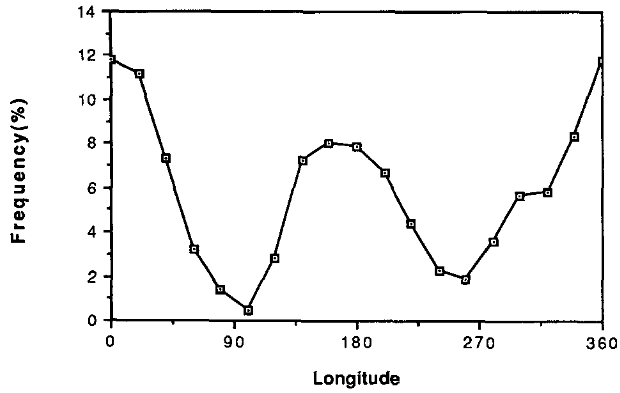

FIG. 1. Longitudinal variation of frequency of blocked 500-hPa flow (%) for the December–May period.

4. Climatology

a. Climatology of blocking

We used the index defined in (4) to study climatology of blocking and computed frequency of blocked flow as a function of longitude for the time period 1 December–31 May. As was done by Lejenäs and Økland (1983), who computed similar statistics for each month of the year, we added another criterion, namely, that the mean value of the index over 30° of longitude should be less than zero. The additional criterion was applied in order to eliminate cases in which only a few negative values showed up in the time–longitude diagram. It is likely that these cases do not represent blocked flow. The statistics are shown in Fig. 1, and the results reflect what Lejenäs and Økland (1983) found for individual months. They also compare to what Rex (1950) and Treidl et al. (1981) found using different criteria.

b. Climatology of traveling wave 1

A number of articles (see, for example, Madden 1978; Madden and Speth 1989) have demonstrated that a traveling component of planetary-scale wave 1 is present during certain time periods and that it propagates westward with a speed of about 16–20 days per revolution around the earth. The ridge of the traveling wave has its maximum at 60°–65°N. A visual inspection of time–longitude diagrams similar to Fig. 2 for the 500-hPa geopotential height at 60°N of our filtered wave revealed that fairly often, during the time period studied, wave 1 propagated westward. During certain time periods, the propagation toward the west was outstanding; during other periods, it was less regular, or absent. Of all available 5238 days (40 missing days) there was a pronounced westward-propagating wave 1 present during 2026 days, that is, during 39% of all days. *Pronounced propagation* is defined as westward propagation that continues for at least 90° of longitude. Madden and Speth looked at a different level (250 hPa) for a different time period (1979–1987) in a different set of analyses (European Centre for Medium-Range Weather Forecasts) and found that westward propagation was evident 38% of the time during December, January, and February (DJF), and 34% of the time during March, April, and May (MAM).

The mean amplitude (at 60°N) of the filtered wave for all 5238 days was 85 gpm, and the variance was 2134. If we assume, conservatively, 8 days between independent estimates (Lorenz 1973; Madden 1976), then the standard error of the mean is 1.8 gpm $\{[2134/(5238/8)]^{1/2}\}$. The corresponding values for the subset of 2026 days when wave 1 moved westward were 92 gpm and 2133, giving a standard error of the mean of 2.9 gpm. We assume 8 days between independent estimates again and in all similar estimates to follow. Madden and Speth (1989) found similar mean amplitudes (96 gpm during DJF and 86 gpm during MAM) of the traveling wave at 500 hPa and 60°N. Ahlquist (1985) computed maximum amplitudes of Rossby mode geopotential fluctuations (Hough functions) at 500 hPa and 40°N during three years of twice-daily NMC global analyses. For zonal wavenumber 1, he obtained amplitudes around 20 gpm for the first three meridional wavenumbers. Our values, at 60°N, will be somewhat larger. Similarly, Lindzen et al. (1984) found amplitudes to be less than 76 gpm for zonal wavenumber 1 Rossby modes at 60°N. A direct comparison between our amplitudes and those of Ahlquist and Lindzen et al. is difficult because ours may reflect a combination of a couple of meridional, global modes, or as Straus et al. (1987) have considered, we may be dealing with disturbances confined to the Northern Hemisphere that have larger projections onto single latitude waves than onto global modes.

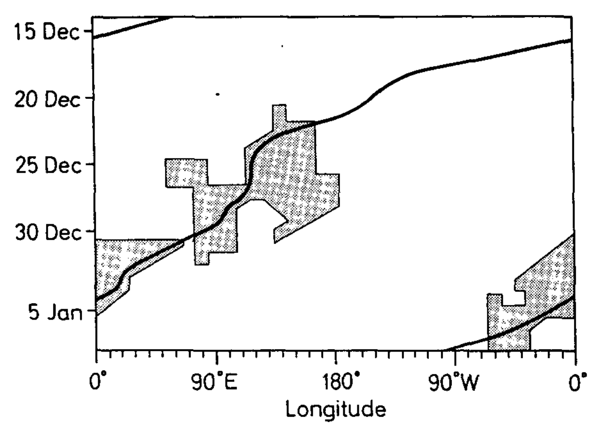

FIG. 2. Time–latitude diagram showing an example of a pronounced westward-propagating filtered wave 1 that occurred at the same time as there was blocking. The full line shows the position of the ridge of filtered wave 1 at 60°N, and shaded areas indicate blocked flow. The time period is 15 December 1954–8 January 1955.

Comparing the filtered amplitude for all days (85 gpm) with that during westward-propagating episodes (92 gpm) indicates that their difference is larger than twice the standard errors of the means, so we might reject a null hypothesis that they are equal with only small chance of error.

c. *Climatology of traveling wave 2*

It has also been demonstrated that a traveling component of planetary-scale wave 2 is present during certain time periods (see, for example, Arai 1981). Arai found that during winter the amplitude of traveling wave 2 has its maximum at 60°N. As for wave 1, we computed time–latitude diagrams for wave 2 and evaluated statistics for the westward-moving wave 2.

Of all available 5238 days, there was a pronounced westward-propagating wave 2 present during 851 days, that is, during 16.2% of all days. There were 58 cases in all. The mean amplitude of the filtered wave 2 during all 5238 days was 78 gpm, and the variance was 2172, giving the standard error of the mean of 1.8 gpm. Ahlquist (1985) found a maximum amplitude of 29 at 40°N for Rossby-mode geopotential fluctuations (zonal wavenumber 2 and meridional wavenumber 2), which is comparable to our values, considering that we computed amplitudes for 60°N. The mean amplitude for all 851 days with a westward-propagating wave 2 was 62 gpm, and the variance was 1303, giving the standard error 3.5 gpm. In this case, the amplitude of the westward-traveling wave 2 is smaller than the overall average amplitude of the filtered wave 2 in a statistically significant sense.

5. The relation between the westward-propagating wave 1 and blocking

a. *Westward propagation in absence of blocked flow*

We indentified time periods with a pronounced westward-propagating wave 1 when there was no blocked flow. Results with blocked flow are reported in the next section. By westward propagation and no blocked flow, we mean a westward-propagating wave whose ridge never comes within 20° of a block during its lifetime. We found 60 cases comprising 656 days with westward-propagating wave 1 and no blocked flow. In these cases, the mean amplitude of the traveling wave was 69 gpm and the variance was 1410, giving a standard error of the mean of 4.1 gpm. Average mean speed, duration, etc., are given in Table 1.

Although not necessarily related to our study of the relation of traveling large-scale waves to blocking, we also wanted to find out if there was a significant difference in characteristics between those waves that traveled a long distance and those that did not. Therefore, we divided the 60 cases into two groups, one with all cases when the filtered wave traveled at least 270° of longitude (12 cases comprising 217 days), and another group with waves that traveled more than 90°, but less than 270° (48 cases comprising 439 days). We found no evidence for a significant difference since the difference in mean amplitude (4 gpm) is not statistically significant in comparison with the standard errors of the mean (7.2 and 5.4 gpm, respectively).

b. *Westward propagation in presence of blocked flow*

Next we identified events with a pronounced westward-propagating wave 1 and blocked flow. They were defined as propagating wave episodes if at some time during the existence of the wave its ridge came within 20° of a block during its lifetime. As for the cases with nonblocked flow, they were found by visual inspection of the time–longitude diagrams. As before, we did not include cases when the wave traveled less than 90° of longitude. We found 95 cases comprising 1370 days, which is 67.6% of all days with a pronounced westward-propagating wave 1 (cf. section 5a) and 26.2% of all days in the dataset. An example of a pronounced westward-moving wave 1 that occurred at the same time as there was a blocking is shown in Fig. 2.

The flow was not blocked at the longitude of the ridge of the traveling wave during all days of an event, and therefore, days with the ridge within 20° of a block were separated from days with the ridge beyond 20° of a block. The frequency of days in the first group as a function of longitude is plotted in Fig. 3 (the curve with open squares). For example, the 3% value at 180°

TABLE 1. Salient features of the westward-propagating wave 1 at 60°N. Standard error is represented by SE and equals the square root of the variance divided by one-eighth of the number of days.

	Number of cases	Number of days	Mean amplitude (gpm)	Variance/SE	Average of turns around earth	Average duration (days)	Average mean speed (days per turn)
No blocked flow	60	656	69	1410/4.1	0.72	12	18
Blocked flow	95				0.83	17	21
Wave 1 within 20° of block		472	121	2573/6.6			
Wave 1 beyond 20° of block		898	88	1715/3.9			

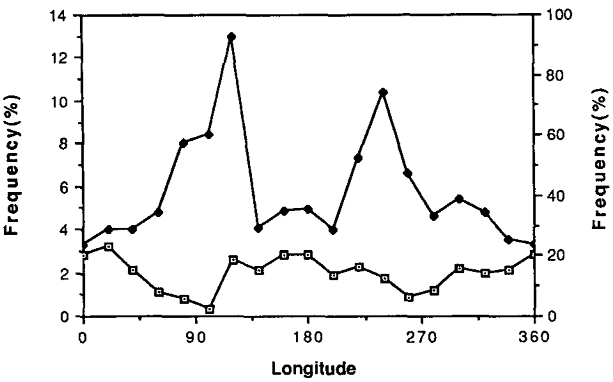

FIG. 3. Longitudinal variation of frequency of a westward-moving wave 1 within 20° longitude of a block (the curve with open squares). The curve with full squares shows the percentage number of times there was a ridge of wave 1 within 20° of a longitude with blocked flow. Note that the numbers for the latter curve are given to the right.

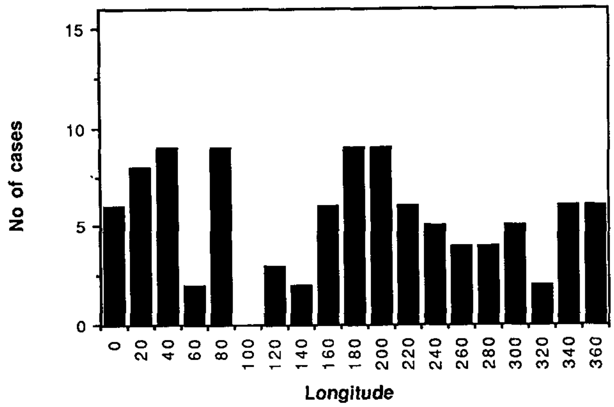

FIG. 4. Longitudinal variation of the number of times a westward-propagating wave 1 lined up with a blocking. The numbers here differ from the data of Fig. 3 because here the ridge of the traveling wave and the block are the *same* longitude.

means that 3% of *all* days were days when a wave was within 20° of a block at that latitude. We note that the frequency does not vary much with longitude except that there are two minima, around 90° and 270°. At these longitudes there are few blockings (cf. Fig. 1). The average frequency is 1.9% of all days. In Fig. 3 we have also plotted how many days with blocked flow wave 1 were within 20° of a longitude with blocked flow (the curve with full squares). The numbers, given in percent, were obtained by dividing the numbers for the other curve in Fig. 3 with corresponding values in Fig. 1. We note that in areas where blockings are frequent (the Atlantic and the Pacific), there is a westward-propagating wave 1 present during 20%–40% of days with blocked flow. In those areas where there are few blocks (around 100° and 260°), a major part of the blocks occur in connection with a westward-moving wave 1.

The mean amplitude, variance, and some other characteristics of the westward-propagating wave 1 during the 95 cases extracted are given in Table 1. We note that the amplitude of wave 1 was more pronounced during blocked flow than nonblocked flow; 121 and 88 gpm, versus 69 gpm, respectively. The variance was 2573 for the first group and 1715 for the second group. Details about average duration, etc., are found in Table 1.

In order to illustrate the behavior of the filtered wave 1 when it approaches the area of blocked flow, we used the 95 cases with a pronounced westward-propagating wave 1 and blocked flow and made composite maps for the 5 days preceding and following that day the ridge first lined up with the block, that is, when it arrived at the longitude of the blocked flow. This occurred all around the earth; the number of cases as a function of longitude is shown in Fig. 4. We note that there are no obvious preferred longitudes, although there is a tendency for more cases in those regions where blocks are most frequent (the Atlantic and the Pacific). Since the geographical area where the ridge of wave 1 lined up with a blocking varies, longitude 0° was defined as the longitude of the *block* for the composites (note: not the longitude of the ridge) in all 95 cases. Here we do not present the maps for wave 1 alone; however, the amplitude of the filtered wave 1 at 40°, 50°, 60°, 70°, and 80°N the day it lines up with the blocking—as well as the five days that precede this day—is plotted in Fig. 5. The results show that the amplitude of the traveling wave 1 at 60°–80°N increases as the wave approaches the blocking from the east. The largest am-

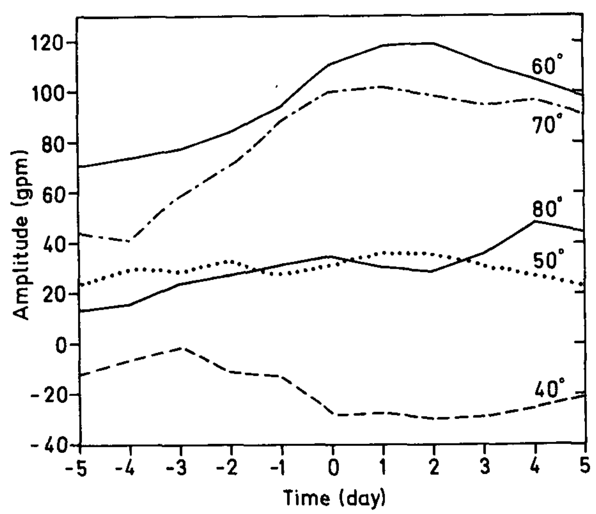

FIG. 5. The geopotential height at the longitude of the ridge of the filtered wave 1 at 40°, 50°, 60°, 70°, and 80°N as a function of time. Day 0 is the day the ridge lined up with the block, and day −5 means 5 days earlier. The heights were obtained from composite maps for wave 1.

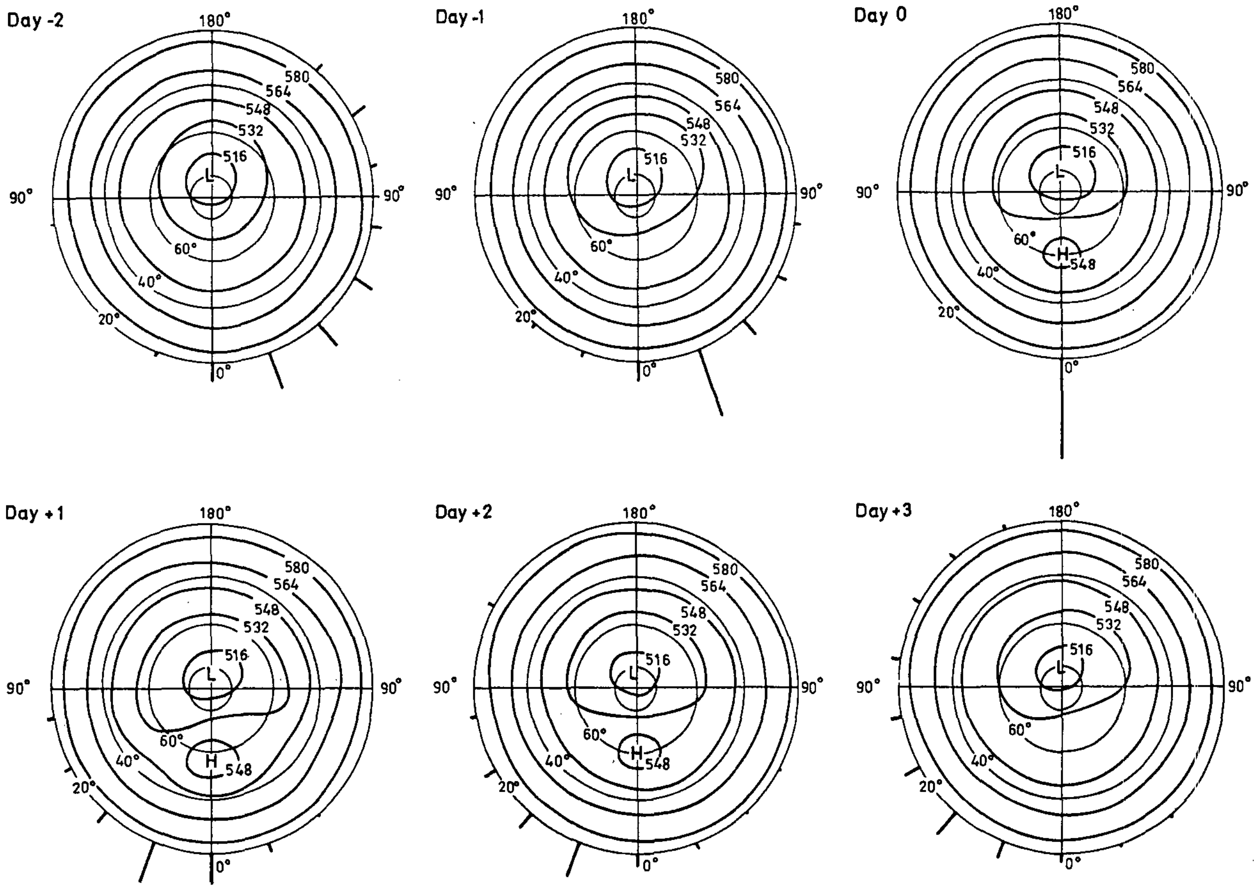

FIG. 6. Composite maps of the 500-hPa flow two (day −2) and one (day −1) days before the ridge of wave 1 lined up with the blocking (day 0); one (day +1), two (day +2), and three (day +3) days after that it lined up with the blocking. The six maps correspond to the composite maps of wave 1. Since the blockings occur at different geographical areas, 0° longitude was used as the longitude for the block. The columns surrounding the maps indicate the longitude for the ridge. The height of each column is proportional to the number of cases.

plitude also persists for at least five days at latitude 60°–70°N, which means that it helps to produce persistent positive anomalies of the kind Dole and Gordon (1983) discussed.

The composite maps of the 500-hPa flow (all 18 wavenumbers) corresponding to these composite amplitudes of wave 1 are shown in Fig. 6. The first sign of a blocking is noticed 1–2 days before the ridge of wave 1 arrives at the blocking. At this day (day 0) we see the characteristic flow pattern during a blocking situation. From the third day after wave 1 lined up with the block (day +3), the blocking starts to weaken. The longitude of the ridge of the traveling wave 1 is indicated with columns surrounding the maps. Necessarily, at day 0, the day the ridge lines up with the blocking, all 95 cases are found at longitude 0°. One (day −1) and 2 (day −2) days earlier, we mostly find the ridge east of 0°, and 1 (day +1), 2 (day +2), and 3 (day +3) days after wave 1 lined up with the ridge, it is mostly found east of 0°. The height of each column is proportional to the number of cases. There are some nonzero columns west of the reference longitude at day −2 and day −1. These represent cases when wave 1 moves eastward just before a westward-propagating episode starts. They are very few and do not influence our results.

6. The relation between the westward-propagating wave 2 and blocking

a. Westward propagation in absence of blocked flow

There were fewer westward-propagating episodes for wave 2 than for wave 1 (16% of all days for wave 2 and 39% for wave 1). As for wave 1, we identified periods with a westward-propagating wave 2 when there was no blocked flow. The results are presented in Table 2. There were 16 cases comprising 189 days with westward propagation in absence of blocked flow. The mean amplitude of wave 2 was 52 gpm, and the variance was 779. Average mean speed, duration, etc., are given in Table 2. The average number of turns is 64% less than

TABLE 2. Salient features of the westward propagating wave 2 at 60°N. Standard error is represented by SE and equals the square root of the variance divided by one-eighth of the number of days.

	Number of cases	Number of days	Mean amplitude (gpm)	Variance/SE	Average of turns around earth	Average duration (days)	Average mean speed (days per turn)
No blocked flow	16	189	52	770/5.7	0.46	10.9	22.8
Blocked flow	42				0.63	14.8	24.7
Wave 2 within 20° of block		102	75	1573/11.1			
Wave 2 beyond 20° of block		560	64	1365/4.4			

for wave 1, (0.46 and 0.72, respectively), and the mean speed is lower for wave 2 (about 79% of the value for wave 1). The average duration is about the same.

b. Westward propagation in presence of blocked flow

A visual inspection of the time–latitude diagrams for traveling wave 2 at 60°N and blocked flow showed that they are sometimes coincident, although not as frequently as for traveling wave 1 and blocked flow. There were 42 cases comprising 662 days, for which blocked flow occurred at some time during the existence of the wave, and its ridge came within 20° of a block. As for episodes with no blocked flow, the average number of turns around the earth is fewer than for wave 1 (0.63 and 0.83, respectively), and the average mean speed is also less (about 85% of the value for wave 1).

Since there was not blocked flow all days during an event, we divided all cases into two groups, one with episodes when wave 2 was not within 20° longitude of a block during its lifetime, and another one with episodes when wave 2 was within 20° of a block during some days of its lifetime. The results are found in Table 2. There were 102 days with wave 2 within 20° longitude of a blocking; the mean amplitude was 75 gpm, and the variance 1573. In regard to the number of days with wave 2 beyond 20° of a blocking, there were 560 days; the mean amplitude was 64 gpm, and the variance 1365. We also investigated if there was any significant difference between episodes when blocking occurred over the Atlantic and when it occurred over the Pacific. We found nothing in our data, however, suggesting that there was a difference.

The mean amplitude of the filtered wave 2 for all days when it propagated westward was 62 gpm (cf. section 5c). The amplitude is slightly pronounced during episodes with blocked flow. The difference is, however, small.

To further investigate the importance of the traveling component of wave 2 for blocking, we plotted the frequency of days when wave 2 was within 20° of a block as a function of longitude. The results are presented in Fig. 7 (the curve with open squares). The frequency varies between 0.2% and 2.1%. In Fig. 7 we have also plotted how many days (of all days with blocked flow) wave 2 was within 20° of a longitude of blocked flow (the curve with full squares). These numbers were obtained by dividing the numbers for the curve with open squares with corresponding values for Fig. 1, and they are given in percent. The frequency is less for wave 2 than for wave 1 (10%–20% compared to 20%–40%). The value for 100° is probably not representative, but reflects the small frequency of blocks there (Fig. 1). Because of the small numbers for wavenumber 2, we did not compute composites analogous to Figs. 5 and 6. We thus conclude that the westward-traveling component of wave 2 is important for some blocking episodes. It occurs, however, less frequently than wave 1.

Finally, it is of interest to know to what extent the cases where wavenumber 2 events coincide with blocking overlap with the cases where wavenumber 1 events coincide with blocking. It turned out that 23% of the days with wavenumber 2 and blocking were in the dataset for wavenumber 1 and blocking. These 23% of cases may reflect that the traveling disturbances have more of a local structure than a global wave structure for those 23% of cases.

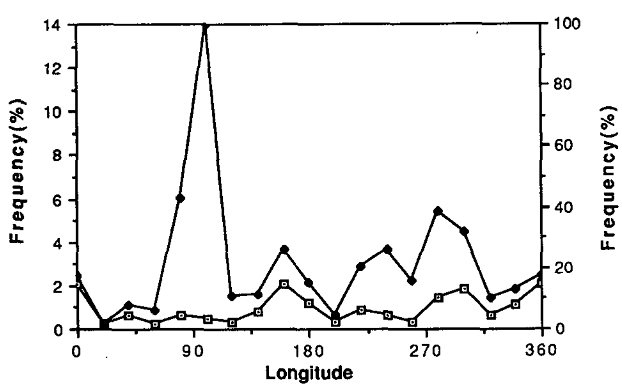

FIG. 7. Longitudinal variation of frequency of a westward-moving wave 2 within 20° longitude of a block (the curve with open squares). The curve with full squares shows the percentage number of times there was a ridge of wave 2 within 20° of longitude with blocked flow. Note that the numbers for the latter curve are given to the right.

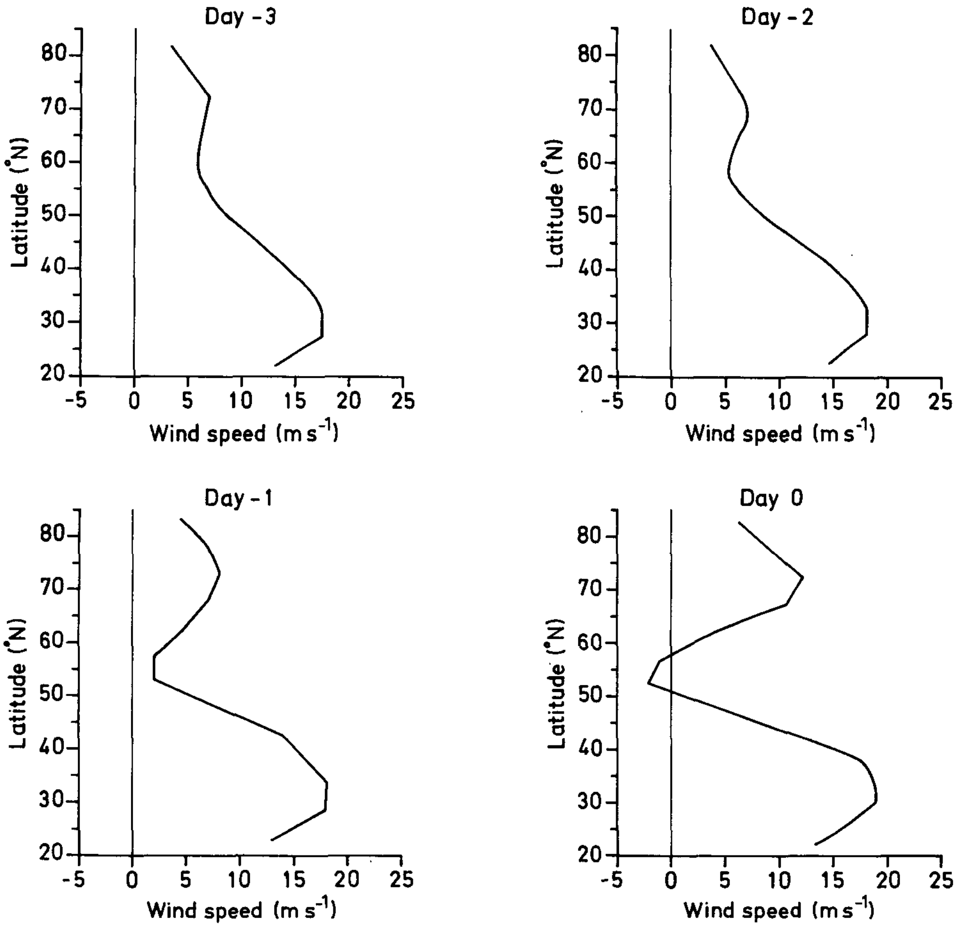

FIG. 8. Zonal geostrophic winds along the longitude where the ridge of wave 1 lines up with the block 3 (day −3), 2 (day −2), and 1 (day −1) days before it arrives at the blocked area (day 0). The values were computed from the composite maps in Fig. 6.

7. Discussion

We have computed the geostrophic winds at the longitude of the block (0°) from the composites of Fig. 6. Figure 8 shows how a split jet is enhanced as the traveling wave 1 approaches from the east. The zonal wind decreases from day −3 to day 0 by 7 m s^{-1} at 55°N and increases by 3–5 m s^{-1} at 30°N and 70°N.[1] This may signify an important dynamic influence related to the frequent coincidence of blocks and westward-traveling wave 1. The average structure of the traveling wave has its maximum geopotential-height amplitude at 60°–65°N (Madden and Speth 1989). One might expect then, at the longitude of the ridge, the decrease in zonal wind at 55°N and the increase at 70°N. This enhanced split jet may be enough to allow the eddy straining mechanism to maintain a block. In a similar vein, Hartmann and Ghan (1980) found zonal-wind reductions in the vicinity of both Pacific and Atlantic blocks. They showed that this resulted in reduced advection by the mean flow of relative vorticity or cold air upstream of the blocks. They found that the scale of the largest single contributor to the wind reduction was zonal wave 1. Dole (1986) found a tendency for retrogression of waves 1 and 2 in the 500-hPa height field before a major amplification. Dole (1989) also found a weakening and a northward shift of the primary jet axis in both Pacific and Atlantic regions beginning a few days prior to his positive cases, which are often associated with blocks. He noted that a second jet frequently also formed over the subtropics. These results are consistent with the enhanced split jet of Fig. 8. There is, however, an inconsistency that we cannot resolve. Dole shows an eastward movement of the wind perturbation while, if the traveling wave were

[1] It is interesting to note that the zonal-wind perturbation on day 0 shows a latitudinal dependence that is qualitatively similar to that of the mode $m = 1$, $n - m = 3$, "16-day" Hough mode (Longuet-Higgins 1968: Fig. 10, $\epsilon = 10$; Kasahara 1980: Fig. 3). This comparison was suggested by a reviewer.

solely responsible, we would expect a westward movement. Of course all blocking situations are not alike, and there is evidence in the literature of westward propagation of minima in the zonal index (500-hPa geopotential height at 35°N minus that at 55°N) that was coincident with some blocks (e.g., Namias and Clapp 1944; Krueger 1954; Hawkins 1955; Lejenäs and Økland 1983).

These speculations are meant to convey the idea that the wave might influence the local dynamics in a substantial way. On the other hand, we cannot exclude the possibility that the frequent coincidence of the traveling wave and blocking is just a kinematic relation. The traveling waves range in period from 16 to 20 days (Madden and Speth 1989; and many others) to even 25 days (Branstator 1987), and they tend to have phase reversals in the geopotential height near 40°N. This situation could contribute to local, blocklike structures, with a persistence on the order of half their periods in concert with Lindzen's caution (1986).

8. Summary

It has been demonstrated that blocking-type flow patterns in the atmosphere can be maintained by synoptic-scale eddies (see Shutts 1986; Egger et al. 1986; Mullen 1987; and references therein). There is, however, also observational evidence (Arai 1981; Quiroz 1987; Lejenäs and Döös 1987) that blockings in some cases are at least coincident with large-scale traveling waves. We used a 30-yr time series of observational 500-hPa geopotential-height data to study the relation between westward-propagating planetary-scale waves 1 and 2 and blocked flow. We found that depending on longitude, 20%–40% of blocks [as defined by the Lejenäs and Økland (1983) criteria] were related to traveling wave 1. The percentage was smaller for wave 2 since there were only 70 days when there may have been a relation with blocking, compared to 404 days for wave 1.

Our study confirms results of earlier studies that suggest a possible important role for large-scale, westward-propagating waves in many blocking episodes. It demonstrates the frequent coincidence of a wave and a block, but does not define the nature of their possible relation. It may be dynamic or purely kinematic. For example, the traveling wave might locally weaken the westerly flow so that the eddy straining mechanism can be more effective in maintaining a block. On the other hand, the coincidence of a westward-traveling wave and a block may simply reflect the kinematic circumstance that the waves can produce relatively long-lived, high-latitude, positive anomalies in geopotential height that meet the definition of a block.

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