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A comparison between planetary-wave flow regimes and blocking

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ABSTRACT

An investigation of the relative similarities in regime classification of an index designed to isolate cases of blocking based upon the kinematic properties of the regional flow, and one which describes the amplitude of the planetary-scale eddy field, is undertaken with observations from 28 Northern Hemisphere winters. The occurrence of blocking patterns persisting 5 days or more over the eastern Pacific is found to coincide in 94% of all cases with the hemispheric flow being characterized by an amplified planetary-scale wave flow regime. However, the occurrence of such an amplitude regime does not necessarily imply the existence of a blocking pattern in the classical sense. In the eastern Pacific, the split flow blocking developed simultaneously with or during an amplified wave regime episode in 30 of 33 cases. Retrogression of blocking patterns to west of the dateline is a frequent occurrence accompanying the decay of amplified planetary-wave episodes. 3/4 of the blocking episodes occurring west of the dateline formed as a part of amplified wave regime events and persisted into their aftermath. Most European blocking episodes (78%) are a part of an amplified-wave flow regime during some part of their life cycle. Blocking in this sector developed along with or during an amplified wave regime in 30 of 51 cases.

1. Introduction

The intraseasonal variability in the position and amplitude of the major large-scale components of the midlatitude circulation has been a topic of interest since the very beginnings of modern meteorology (e.g., Rossby et al., 1939). Interest in understanding and forecasting this variability has motivated many studies intended to demonstrate the existence of recurrent, persistent flow patterns or flow regimes (for early literature, see Elliot (1951), Baur (1951) and more recently Dole (1986), Mo and Ghil (1988), Molteni et al. (1990)). Early approaches to this problem included the concepts of the index cycle (e.g., Namias, 1950) and blocking (e.g., Rex, 1950a, b). If atmospheric motion could be classified in a few recurrent regimes, attempts at predicting their occurrence at medium and extended range could be possible because of their limited number and persistent nature (e.g., Molteni and Tibaldi, 1990).

Blocking is perhaps the best known example of a flow regime. It is traditionally identified based upon a set of subjective criteria. Obviously, any modification of these criteria will change the classification scheme leading to a degree of arbitrarily. Moreover, subjective criteria may not be immediately suggestive of the physical mechanisms underlining the regimes.

A few years ago (Hansen and Sutera, 1986), we investigated whether an index based on a theory of multiple metastable equilibria (e.g., Charney and DeVore, 1979; Wiin-Nielsen, 1979) could be used for the purpose of obtaining a gross classification of large-scale flow patterns. Since the theory predicted as many flow regimes as there are maxima in the probability density distribution (pdd) of the amplitude of planetary-eddy field (Benzi et al., 1984), we associated distinct regimes

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with each maxima of the wave-amplitude index pdd. Two such maxima were found. This result leads to an important implication.

The minimum separating the two maxima in the wave amplitude pdd can be interpreted as a region of *instability* in the phase space of all possible atmospheric flow configurations. If there is a relationship between the planetary-wave amplitude and regional flow regimes like blocking, it may be possible to understand the dynamics of blocking within the context of the implied instability in the large-scale flow.

Thus, the purpose of the present study is to investigate the relative similarities in regime classification of an index designed to isolate cases of blocking and one which by its definition describes the amplitude of the planetary-scale eddy field. The outcome of this comparison is not obvious since the wave amplitude index is of hemispheric scale while blocking is conventionally thought of as a regional flow anomaly. We will compare the wave amplitude index of Hansen and Sutera (1986) to the index of blocking devised by Lejenäs and Økland (1983) (hereafter referred to as the LO index). The LO index is based on Rex' (1950a) classic blocking definition and is similar to the traditional definition of the zonal index (Namias and Clapp, 1951).

2. Data

Two datasets are used in the present study. The first consists of once daily (12 GMT) 500 mb height analyses prepared by the National Meteorological Center (NMC) from 1 January 1960 through 31 December 1980. The second consists of the 500 mb height analyses prepared twice daily (00 and 12 GMT) by the European Centre for Medium-range Weather Forecasts (ECMWF) for the period from 1 January 1980 through 31 December 1988. These datasets span a total of 28 Northern Hemisphere winters (1 December through 28 February) for a total of 2520 days of data. The NMC data were interpolated from the NMC octagon grid to a 5° by 5° latitude/longitude grid and span 20 NH winters (1960–61 through 1979–80). The ECMWF data span the final 8 winters (1980–81 through 1987–88) and were obtained on the spectral transform grid of a rhomboidal wavenumber 15 truncation of the data. Thus, the horizontal resolution of these data grids are 7.5° longitude by roughly 4.4° latitude.

3. Index computation

3.1. Planetary wave amplitude index

The wave amplitude index is computed as follows. For once daily 500 mb height grids, the grid point heights, $z(\lambda, \phi)$, are averaged with respect to latitude, ϕ, within the zone of largest planetary wave variance (in this case 45° N–70° N), yielding an array of meridionally averaged heights as a function of longitude, λ. These heights are then Fourier decomposed with respect to longitude and the amplitude index computed for zonal wavenumbers 2 through 4:

$$[Z_{2-4}] = \left(\sum_{m=2}^{4} 2Z_m^2 \right)^{1/2},$$

where Z_m denotes the complex Fourier height coefficient for zonal wavenumber m. The resulting time series has the very simple physical interpretation of representing the time behavior of the root-mean-square planetary-wave amplitude for the chosen zonal scale for the latitude averaged geopotential height within the latitude zone where that variability is largest. The time series is filtered to remove the annual cycle and high frequency variance with periods shorter than 4 days. An estimate of its probability density distribution (pdd) is computed (see Hansen and Sutera, 1986, 1988, 1990 for details). This pdd exhibits two modes as illustrated in Fig. 1 for the 28 winters used in the present study.

The wave amplitude index achieves an objective regime classification based upon the location of the minimum in the bimodal pdd (e.g., Hansen and Sutera, 1986). One regime is a low wave-amplitude regime (or mode-1 regime) and the other a large wave-amplitude regime (or mode-2 regime). When the wave amplitude exceeds the value at the minimum in Fig. 1 on a given day, the flow is assigned to the mode-2 regime. Otherwise, it is assigned to the mode-1 regime. Approximately 40% of all winter grids fall into the mode 2 or large wave amplitude regime.

The choices of wavenumber band and latitude zone used in constructing the index are based upon

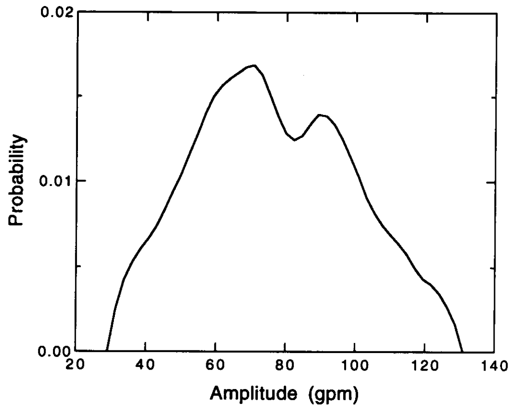


Fig. 1. Probability density distribution of the wave amplitude index for the 28 NH winters (1960–61 through 1987–88). The abscissa units are the rms wavenumber 2–4 amplitude in geopotential meters averaged in the 45° N–70° N zone.

the nonlinear theory of low frequency variability (e.g., Benzi et al., 1986a, b, 1988) and the empirical distribution of wave variance, respectively. Recent GCM results indicate that essentially identical classifications can be obtained through an empirical orthogonal function analysis in which no choices concerning the temporal or spatial scale of the variance are made (Hansen and Sutera, 1992).

3.2. *Blocking index*

An objective comparison of these wave amplitude regimes to blocking is accomplished by employing the LO blocking index. This index exploits the classic subjective definition of blocking (Rex, 1950a) which is based on the kinematic properties of the regional flow and on persistence. (A similar index was applied to the Southern Hemisphere by Lejenäs (1984) and to the question of blocking persistence by Økland and Lejenäs (1987).)

Succinctly, the LO index is simply the difference in 500 mb height between 40° N and 60° N averaged over grid points spanning 30° longitude. If the index is negative, mean geostrophic easterlies are implied in the zone as higher heights would exist at 60° N than at 40° N. Thus, if the index is negative on a given day within a given sector, that day is classified as a blocking day. As with other definitions of blocking (e.g., Austin, 1980; Charney et al., 1981; Treidl et al., 1981), the specification of the criteria which constitute blocking in the LO index is subjective. Once specified, however, their application is simple and objective. Because of its definition, the LO index best identifies blocking anticyclones located at 60° N. Other cases with the anticyclone located further north (or south) can be missed. Thus the LO index can be viewed as identifying a large subset but not all of the total number of blocking days.

The present datasets have a different spatial resolutions, so the blocking index at longitude λ, $I(\lambda)$, was computed as follows:

$$I(\lambda) = Z_{40N}(\lambda) - Z_{60N}(\lambda).$$

For the ECMWF data, the height for 40° N is computed as the mean of the heights at 37.8° N and 42.2° N. To avoid spuriously brief (one day) duration negative indices, the blocking index is averaged with respect to longitude, so that the blocking index within a sector is given for the ECMWF data by

$$I(\lambda') = I(\lambda - 7.5) + I(\lambda) + I(\lambda + 7.5) + I(\lambda + 15),$$
$$\lambda' = \lambda + 3.75,$$

and for the NMC data (as in LO) by

$$I(\lambda') = I(\lambda - 10) + I(\lambda) + I(\lambda + 10).$$

Blocking is said to occur if $I(\lambda')$ is negative. A time series of the LO index was computed for each longitude line in the data grids. The LO index reasonably reproduces the climatology of blocking occurrence compared to other approaches, even though it does not explicitly include the 10 day persistence criterion used by Rex (Lejenäs and Økland, 1983).

4. Results

4.1. *Classification comparison*

Results for the percentage of winter days identified as blocked based on the LO index as a function of longitude for the 28 winters studied is consistent with previous studies (not shown). Blocking is most frequent in NH winter over the Pacific Ocean and over the eastern Atlantic Ocean and Europe (Rex, 1950b; Treidl et al., 1981; Lejenäs and Økland, 1983). A comparison of the percentage of days classified as blocking by the LO

Table 1. *Percentage of LO blocking days classified as mode 2 days for longitudes where at least 4% of the days are classified as blocked*

	Pacific sector			Atlantic/European sector	
longitude	ECMWF %	NMC %	longitude	ECMWF %	NMC %
120°E	—	24	50°W	—	20
130°E	22	23	40°W	—	34
140°E	16	26	30°W	—	46
150°E	20	33	20°W	43	57
160°E	26	38	10°W	45	66
170°E	38	41	0°	50	71
180°	46	48	10°E	53	71
170°W	46	55	20°E	57	67
160°W	70	68	30°E	47	62
150°W	78	73	40°E	37	63
140°W	95	69	50°E	48	57
130°W	—	71	60°E	54	59

index that also correspond to the amplified wave regime is given in Table 1 for these two sectors. The results of comparing days associated with the amplified wave regime and those identified as blocking for longitudes where blocking occurs on at least 4% of the days are given for both the ECMWF and NMC datasets for comparison. (The ECMWF results were interpolated to 10° latitude intervals for Table 1.) If there were no relationship between LO blocking days and the amplified wave regime all of the entries in Table 1 would be near 40%, the percentage of amplified wave regime days in the datasets. However, in the regions of maximum blocking occurrence over the eastern Pacific Ocean roughly 70% of blocking days are also identified as amplified wave regime days. Over the European sector, blocking days correspond with the amplified wave regime roughly half the time in the ECMWF data but 60–70% of the time in the NMC data. On the other hand, west of the International Dateline over the western Pacific and northeastern Asia, blocking days correspond to amplified wave regime days more infrequently than would be expected if the two phenomena were independent of each other.

Note that the statistics in Table 1 were compiled by considering blocking on individual days and at individual longitudes in isolation. Of course, days and longitudes identified as blocked by the LO index tend to cluster in space and time to form blocking episodes (Lejenäs and Økland, 1983). A more revealing comparison can be made by examining the individual cases of blocking with cases of the mode 1 and mode 2 regimes.

4.2. *Comparison of cases over the Pacific*

Upon closer inspection of the results, individual blocking episodes that developed over the eastern Pacific or near the Dateline overlap with amplified wave regime episodes for all or part of their life cycle (in events lasting 5 days or more) in 31 out of 33 cases (94% of the cases, Table 2). However, the existence of a mode 2 flow regime doesn't necessarily imply the existence of a blocking pattern in the classical sense. These results agree with a subjective comparison of blocking cases to

Table 2. *Summary of blocking cases in relation to the wave regimes*

			Overlapping mode 2	
Blocking location	mode 1 entirely	mode 2 entirely	mode 1 initially	mode 2 initially
east Pacific	2	13	1	17
west Pacific	6	0	0	4
Atlantic/ European	11	17	10	13

The numbers in the columns are the number of cases of blocking in each sector corresponding to each category. The two right-hand columns refer to blocks which overlapped mode 2 regimes but developed during mode-1 or mode-2 regimes, respectively.

the wave regimes from a small subset of the present data (Hansen, 1986).

The eastern Pacific blocking developed either simultaneously with or during an amplified wave regime episode in 30 of the 33 cases. In general, the blocking in this region tends to develop *after* the initiation of an amplified wave regime episode. Moreover, in 15 of 17 cases in which the blocking persisted after the decay of a mode 2 event, the blocking retrograded to a position west of the dateline.

Only 10 cases of LO blocking developed west of the dateline in the 28 winters studied and 4 of these occurred while the hemispheric flow was characterized by the amplified planetary-wave regime (Table 2). Thus, in 19 of 25 (76%) cases with blocking west of the dateline, the blocking developed initially as a part of an amplified wave regime. The low correspondence between individual blocking days and mode-2 days in Table 1 therefore does not imply that there is no relationship between blocking in that sector and the planetary-wave regimes. In summary, 35 of 43 (81%) blocking cases in the entire Pacific sector that persisted 5 days or more developed as a part of the amplified planetary-wave regime.

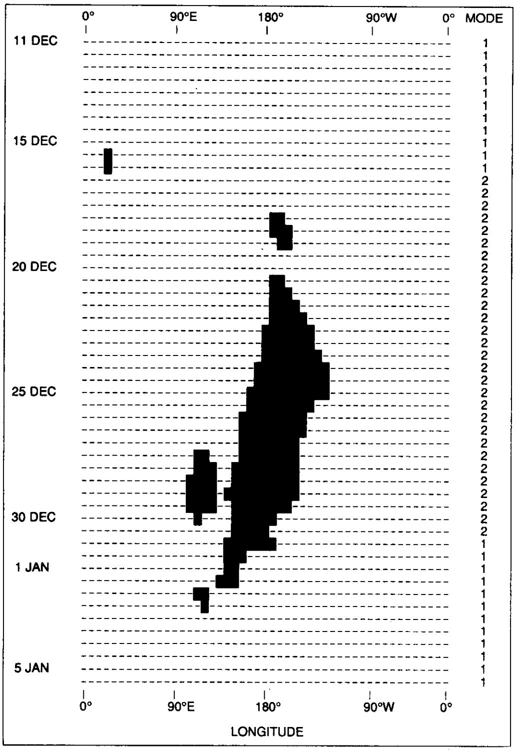
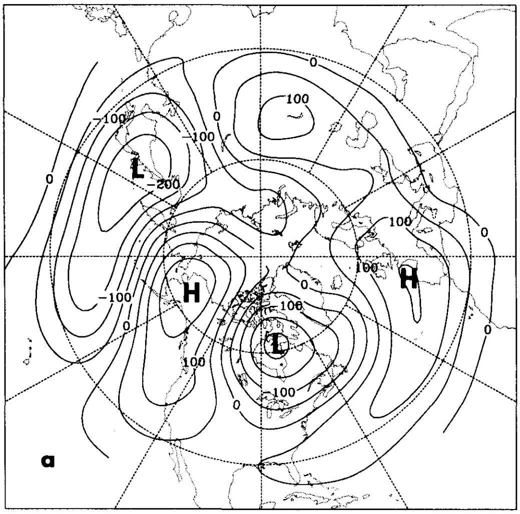


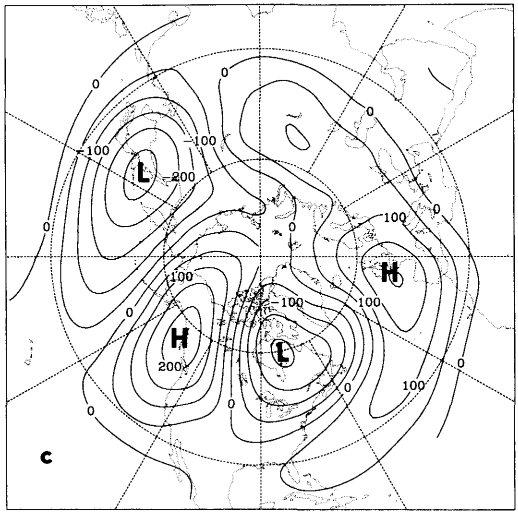
Fig. 2. Longitude-time section of the LO blocking index and the wave-amplitude classification for 11 December 1983 to 5 January 1984. A black box indicates that a longitude on that date is classified as blocking and a "—" indicates no blocking. The 1 or 2 on the right-hand side of the figure indicates whether the indicated date was classified as belonging to the mode-1 or mode-2 wave amplitude-regime respectively.

Synoptically, a typical Pacific blocking case evolves as follows. A mode-2 regime develops with the amplification of a large-scale ridge over the eastern Pacific Ocean. In some cases, subsequent synoptic developments lead to the formation of split-flow dipole blocking in this region after the ridge has amplified. As the wave regime decays, the blocking may also decay, but frequently the blocking pattern tends to retrograde and continue to persist west of the dateline after the planetary waves have decayed. An example of this behavior is given in Fig. 2 for a case from December 1983 to early January 1984. In this case, an amplified wave event developed in mid-December with a dipole blocking structure identified by the LO index forming 1 day later. The amplified wave event persisted until the end of the month and the slowly retrograding blocking pattern persisted as well. The blocking continued to retrograde west of the dateline and finally decayed 3 days after the end of the amplified wave event. In other cases, the blocking persisted in this region for a week or more.

4.3. *Comparison of cases over the Atlantic and Europe*

Over the Atlantic and European sector, the comparison between LO blocking and the wave amplitude regimes is less systematic than over the Pacific. Of the 51 total LO blocking cases in the Atlantic/European sector in the 28 winters, 40 (78%) were entirely or partially included in mode-2 regime events (Table 2). Of these, 17 cases started and ended as a part of a mode-2 regime. Of the remaining 23 cases which overlapped mode-2 regime events for part of their life cycle, 13 blocks formed at or after the onset of an amplified wave regime. Thus a total of 30 cases (or 59%) developed as a part of an amplified wave event. This characteristic is less common in the Atlantic/European sector than it was in the Pacific sector. 10 blocking cases were initiated during the low





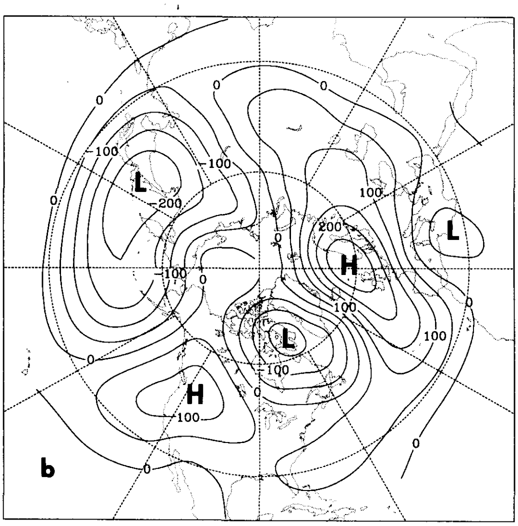


Fig. 3. Polar stereographic maps of the composite 500 mb eddy geopotential heights for (a) Pacific (168° W) blocking days, (b) European (11° E) blocking days, and (c) amplified-wave regime days. Contour interval is 50 m.

wave-amplitude regime and subsequently overlapped a large wave-amplitude regime. The consistent pattern of retrogression of the blocking during or after the decay of mode-2 events that is characteristic of the Pacific cases is not found consistently in the Atlantic/European sector.

21 of the 51 Atlantic/European blocking cases (or 41 %) originated when the hemispheric-scale flow was characterized by the low planetary-scale wave amplitude regime. In contrast, in the Pacific sector a total of only 9 cases of blocking (out of 43 or 21 %) started during a mode-1 regime and 6 of these were west of the dateline. It is possible that these "mode-1 blocking" cases develop from some mechanism that is independent of the dynamics of the amplified planetary wave regime. Possible mechanisms for this type of blocking are discussed, for example, by Green (1977), Illari (1984), Shutts (1983, 1986) and Hoskins et al., (1983), and in observational case studies, for example, by Hansen and Chen (1982), Colucci (1985) and Mullen (1987).

4.4. *Comparison of 500 mb height signatures*

To illustrate the relative influence of the amplified wave regime compared to blocking on the 500 mb height field, composite heights were constructed from all of the LO identified blocking days from the present ECMWF dataset for the longitude sectors of most frequent blocking occurrence over the Pacific Ocean (east of the dateline) and in the Atlantic/European sector (i.e., 168° W and 11° E in that dataset). Maximum time-averaged eddy heights of over 150 m to over 250 m are obtained by the blocking highs (Fig. 3a, b). The amplified wave regime achieves a comparable amplitude in its east Pacific ridge (Fig. 3c) for episodes lasting 5 days or more in a larger ensemble than either of the blocking composites (Fig. 3c represents 24 % of the ECMWF dataset compared to 12% for either Fig. 3a or 3b). The more southerly position of the ridge in the mode-2 ensemble may explain the relatively less frequent occurrence of a strong split flow for the composite of all mode-2 days. On the other hand, the precise position of the features in the blocking composites is somewhat artificial due to the definition of blocking employed in constructing them. Nonetheless, there is a visible correspondence in phase and amplitude between the major features of the Pacific blocking composite and the amplified-wave regime composite including the deep trough over eastern North America.

5. Conclusions

From an analysis of 28 winters of NH 500 mb height data, an investigation of the relative similarities in regime classification of an index designed to isolate cases of blocking based upon the kinematic properties of the regional flow, and an index which describes the amplitude of the planetary-scale eddy field was undertaken.

We conclude that the occurrence of blocking patterns persisting 5 days or more over the eastern Pacific is, in nearly all cases, the result of the hemispheric flow being characterized by an amplified planetary-scale wave flow regime. However, the occurrence of such an amplitude regime does not necessarily imply the existence of a blocking pattern in the classical sense. In the eastern Pacific, the split flow blocking develops simultaneously with or during an amplified wave regime episode in 30 of 33 cases. Retrogression of blocking patterns to west of the dateline is a frequent occurrence accompanying the decay of amplified planetary wave episodes. 3/4 of the blocking episodes occurring west of the dateline formed as a part of amplified wave regime events and persisted into their aftermath. This implies that synoptically the decay of mode-2 events can be accompanied by the retrogression of the mode-2 eastern Pacific ridge and the resultant formation of a cut-off high over northeastern Asia.

Most European blocking episodes (78%) are a part of an amplified-wave flow regime during some part of their life cycle. Blocking in the Atlantic/European sector developed simultaneously with or during an amplified-wave regime event in 30 of 51 cases, or 59% of the total.

The amplified planetary wave amplitude flow regime was identified previously by stratifying observations based upon the existence of a minimum in the zonal wavenumber 2–4 amplitude probability density distribution. The presence of a minimum in this distribution implies the existence of an instability in the large-scale flow. The close correspondence between the amplified wave flow regime and blocking found in this study (in terms of overlapping events and comparable height patterns), particularly over the North Pacific Ocean, emphasizes that the dynamics of these blocking cases may be understood within the context of a theory built around an instability in the large-scale flow. As discussed in Benzi et al. (1986a), a theory which is consistent with the observations requires that the large-scale, low-frequency anomalies of the atmospheric circulation be interpreted as finite amplitude, non-linear free modes essentially confined in midlatitudes (e.g., Benzi and Malguzzi, 1992) and interacting with the lower boundary stationary forcing which acts as a catalyzing agent (fixing the phase) in the formation of the anomaly. Therefore, the present paper implies that a large portion of the intraseasonal, low-frequency variability which manifests itself as large anomalies of the NH winter circulation may be understood as the nonlinear balance of the motion which has its sources and sinks in midlatitudes.

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