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On the definition and persistence of blocking

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ABSTRACT

In this paper, we have investigated under what conditions positive geopotential height anomalies can be interpreted as blocking structures. Furthermore, we have studied the persistence of blocking. The data used here are the observed daily 500 hPa geopotential heights for 10 winter seasons from 1982/83 to 1991/92. The objective blocking criteria of Dole (1978) have been compared with the subjective blocking criteria established by Rex (1950a, b). Our study indicates that if we want to relate positive geopotential height anomalies to blocking as defined by Rex, not only the amplitude, but also the latitudinal position of the anomalies is important. Positive anomalies centered at about 45° N represent a northward extension of the subtropical anticyclone. Large positive anomalies centered at about 60° N are accompanied with negative anomalies at low latitudes and blocking anticyclones centered at about 50° N. We found that blocking and strong zonal flow have the same anomaly pattern but with opposite sign. The day-to-day changes in geopotential height associated with blocking are computed and the relevance of these day-to-day changes to the persistence of the blocking pattern is examined. We find that the day-to-day changes are smaller than normal over the blocking area, but larger than normal north of it. The anomalous day-to-day changes are mainly caused by the northward shift of the jet stream and the corresponding shift in the track of the transient weather disturbances. The strength of the day-to-day changes depends very much on the exact latitudinal location where the changes are computed. These results indicate that the day-to-day changes in geopotential height do not contain information about the persistence of the blocking pattern itself, but merely about the shift of the transient eddies caused by the blocking pattern. Hence, we can not simply interpret the persistence of blocking in terms of the day-to-day changes in positive anomalies. The persistence of blocking and strong zonal flow has been examined. As blocking and strong zonal flow are associated with approximately the same anomaly pattern but with opposite sign, the persistence of blocking and strong zonal flow can be expressed in terms of the duration of the corresponding anomaly patterns. We have shown that the average duration of the blocking and strong zonal flow patterns is approximately the same. This leads us to conclude that although the daily changes in geopotential height are small near the center of the blocking high, the blocking regime itself is not more persistent than the strong zonal flow regime. The persistence of blocking and strong zonal flow has also been compared with a first-order Markov process. Generally speaking, we find no significant differences in persistence between the blocking and strong zonal flow regimes and the first-order Markov process. This leads us to conclude that blocking is not more persistent than other atmospheric anomalies of the same geographical scale. This is in agreement with Lindzen (1986).

1. Introduction

Atmospheric blocking is a typical large-scale circulation feature with a characteristic time scale larger than the synoptic time scale. A better understanding of the blocking phenomenon will deepen our understanding of the low-frequency variability of the atmosphere and perhaps increase our skill in medium-range weather forecasting. Since the early work of Elliot and Smith (1949) and Rex (1950a, b), the blocking phenomenon has received considerable attention for more than 40 years. However, our understanding of it is far from complete. One of the obstacles in studying atmospheric blocking is the definition of blocking itself. There is as yet no universally accepted or widely applied definition of blocking. As pointed out by Mullen (1989), this uncertainty is a major difficulty that confronts researchers and hampers intercomparison of scientific results. The most commonly used characterizations of blocking are the subjective criteria as established by Rex (1950a, b) and the objective criteria defined by Dole (1978). Rex (1950a, b) characterized blocking in terms of the shape of the 500 hPa height fields. He emphasized the split of the jet flow, the sharp transition from westerly to meridional flow and the persistence of the blocking pattern. Dole (1978) identified blocking as large 500 hPa geopotential height anomalies lasting for a sufficient length of time. While Dole's characterization has the advantage of being objective and therefore can easily be applied to large data sets, it is important to recognize that the occurrence of a persistent positive anomaly does not necessarily mean the existence of a blocking high. As pointed out by Charney et al. (1981) "Persistence of an anomaly by itself does not guarantee the persistence of a ridge. For example, if the intensity of the Aleutian low is very weak compared to normal, it may show a large positive anomaly and a weaker seasonal ridge may show a negative anomaly. Thus the simultaneous occurrence of a positive anomaly over the Aleutian low and a negative anomaly over the west coast of North America can be associated with a stronger zonal flow rather than a blocking configuration." Although this is almost trivial and has been noticed for a long time (Charney et al., 1981; Shukla and Mo, 1983), not much work has been done to investigate the conditions that positive anomalies have to satisfy in order to justify the interpretation of positive anomalies in terms of blocking structures.

Another quite confusing aspect of blocking is its persistence. Persistence of blocking has been interpreted in two different ways, namely, (1) in terms of the day-to-day changes in positive geopotential height anomalies in some pre-chosen area (Horel, 1985), and (2) in terms of the duration of the blocking pattern itself (Rex, 1950a, b; Dole and Gordon, 1983; Blackmon et al., 1986).

Horel (1985) has studied the day-to-day changes in positive geopotential height anomalies over the central Pacific and interpreted these changes as the daily variations in the amplitude of the blocking pattern. He showed that negative anomalies of about -100 m to -200 m over the central Pacific tend to exhibit less change during the following few days than large positive anomalies. He therefore concluded that if the variable amplitude of blocking is considered, blocking over the central Pacific is less persistent than strong zonal flow. However, interpreting the persistence of blocking in terms of the day-to-day changes in positive anomalies, it is important to note that these changes are not only caused by the changes in the amplitude of the blocking pattern, but also reflect the effect of the transient weather disturbances. It is well known that blocking has a significant effect on the high-frequency transient weather disturbances. Blackmon et al. (1986) and Dole (1986a) have shown that the activity of the transient weather disturbances is weakened near the center of the blocking high and enhanced north of it. By looking at day-to-day changes in positive geopotential height anomalies, we are also sampling information with respect to the activity of transient eddies. Also, as will be shown in this paper, the strength of the day-to-day changes depends very much on the exact latitudinal location where the changes are computed. So we can not simply interpret the persistence of blocking in terms of the day-to-day changes in positive anomalies.

The persistence of blocking has also been expressed in terms of the duration of the blocking flow pattern itself. There is no doubt that blocking tends to persist longer than the much smaller scaled synoptic disturbances (Rex, 1950a, b; Dole and Gordon, 1983; Dole 1986a, b). However, as pointed out by Lindzen (1986), this comparison is not particularly relevant in view of the dissimilar scales. Persistence ought to mean long lasting compared to the time scales expected from transients of the same geographical scale, for example, the large-scale strong zonal flow regime. Dole and Gordon (1983) have examined the Northern Hemisphere blocking and strong zonal flow activities for the 14 winter seasons from 1963/64 through 1976/77. They show that whereas for the unfiltered data the number of persistent positive cases ($+100$ m, 10 days) exceeds the number of persistent negative cases (-100 m, 10 days), for the low-pass filtered data the numbers of positive and negative cases are comparable. Actually, Fig. 6 of Dole and Gordon (1983) even shows that both in the Atlantic and Pacific areas, the number of persistent negative cases slightly exceeds the number of persistent positive cases. This result indicates that although strong zonal flow exhibits more brief transient interruptions than blocking, the duration of the zonal flow regime itself is not necessarily shorter than the blocking regime. This result also indicates that in order to establish the persistence of blocking relative to the persistence of strong zonal flow, we must distinguish the daily variabilities due to the transient weather disturbances from the degree of persistence of the flow regimes themselves.

In this paper, we have investigated under what conditions positive anomalies can be interpreted in terms of blocking structures and we have studied the persistence of blocking. With respect to persistence of blocking we have investigated the relevance of day-to-day changes in geopotential height and we have looked at the degree of persistence of the large-scale dipole-like anomaly pattern which characterizes blocking, relative to the persistence of strong zonal flow, which is characterized by the same anomaly pattern with opposite sign. The data used in this study are described in Section 2. In Section 3, we show that only large positive geopotential height anomalies centered at about 60° N can be associated with the blocking pattern as described by Rex. Large positive anomalies centered at about 45° N represent a northward extension of the subtropical anticyclone. In Section 4, the day-to-day changes in geopotential height associated with blocking and strong zonal flow over the North Atlantic have been studied. In Section 5, the persistence of the blocking and strong zonal flow have been examined in terms of the duration of the large-scale anomaly patterns that determine those regimes. The conclusions are summarized in Section 6.

2. Data

The data used here are the Northern Hemisphere daily (12 GMT) 500 hPa geopotential height analyses from the European Center for Medium Range Weather Forecasts (ECMWF) for the 10 winter seasons from 1982/83 to 1991/92. The winter season consists of December, January and February. The number of longitudinal points is 64 for each line of latitude. The number of latitudinal points is 16 for the Northern Hemisphere. A few days with missing data are filled in by linear interpolation in time. The climatological mean value at each grid point has been computed by averaging the corresponding daily geopotential height value of the 10 winters. Geopotential height anomalies at each grid point for each day of the 10 winter seasons have been computed as the departures of the daily analyzed values from the corresponding mean values.

3. Large positive geopotential height anomalies and blocking

According to Rex (1950a, b), blocking is a situation in which the normal eastward progression of migrating midlatitude weather systems is obscured, or blocked, by the development of a high-amplitude, quasi-stationary anticyclone. The main purpose of this section is to investigate the relationship between the geographical location of large positive geopotential height anomalies centered at various latitudes and the blocking pattern as subjectively defined by Rex and many others (e.g., Elliott and Smith, 1949; Sumner, 1954; Austin, 1980; Treidl et al., 1981). For each day, the latitudinal mean anomalies of 500 hPa geopotential height over the Atlantic and western European areas have been computed at 30° N, 45° N and 60° N. As shown in Fig. 1, each of the latitudinal mean anomalies is computed by averaging the daily geopotential height anomalies at 16 grid points from about 55° W to 30° E. We call these time series ZA30, ZA45, ZA60 respectively.

For each time series, the 200 days with the largest positive geopotential height anomalous values have been selected. The mean state of these 200 days and their anomalies from the climatological mean have been computed. Fig. 2a shows the mean of the 500 hPa geopotential height for the 200 days with the largest positive anomalous values of ZA60. It displays the typical blocking pattern as defined by Rex. The center of the blocking high is located at about 50° N. The anomaly pattern of Fig. 2b is dominated by a strong positive anomaly centered at about 60° N and a negative anomaly south of it. The height gradient has been enhanced north of the positive anomaly center and weakened south of it, leading to a stronger than

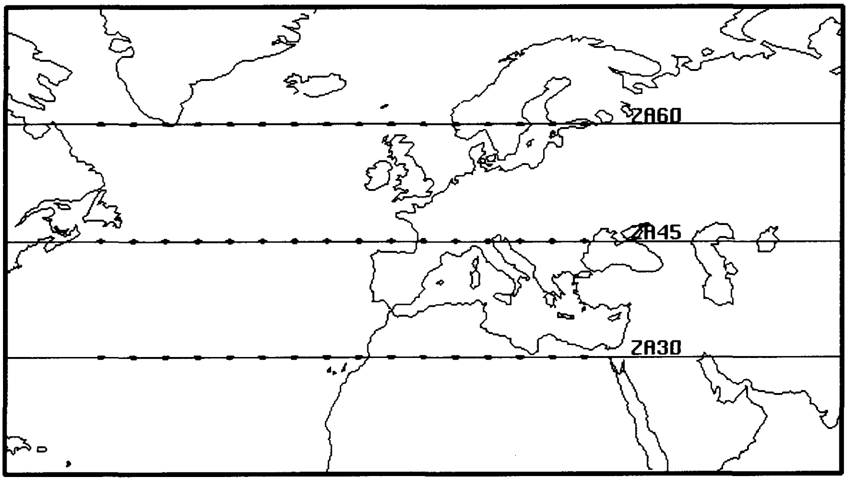


Fig. 1. Locations of the grid points used to computed the latitudinal mean anomalies of 500 hPa geopotential height at 30° N (ZA30), 45° N (ZA45) and 60° N (ZA60).

normal jet stream north of 60° N and a weaker than normal jet stream south of 60° N. Notice that the latitudinal location of the blocking anticyclone center does not coincide with the location of the positive anomaly center. The blocking anticyclone center is located about 10° south of the positive anomaly center.

Fig. 3a, b shows the mean and the anomalies of the 500 hPa geopotential height for the 200 days with the largest positive anomalous values of ZA30. The mean field over the North Atlantic is a typical high zonal index flow. The North Atlantic is dominated by a strong trough and a stronger than normal jet stream. The anomaly pattern of Fig. 3b is almost the opposite from the anomaly pattern of ZA60. It is characterized by a large negative anomaly centered at 60° N and a positive anomaly south of it. This result indicates that blocking and strong zonal flow regimes over the North Atlantic are associated with approximately the same anomaly pattern but with opposite sign. This is in agreement with Dole (1986a). He shows that to a first approximation, the composite anomaly patterns of the positive and negative geopotential height anomaly cases for a given region can be described as opposite phase of the same basic pattern. Also in his study, the positive anomaly cases are often associated with blocking flows and the negative anomaly cases are related to regionally intensified zonal flows.

Fig. 4a, b shows the mean and the anomalies of the 500 hPa geopotential height for the 200 days with the largest positive anomalous values of ZA45. We see that positive anomalies centered at about 45° N are related to the northward extension of the subtropical anticyclone. The whole jet stream over the North Atlantic area has shifted northward but there is no sign of a split in the jet. Actually, the jet stream is stronger than the climatological mean over most parts of the North Atlantic area. Apparently, this kind of circulation can not block the normal eastward progression of migrating midlatitude weather systems. We may therefore conclude that large positive anomalies centered at about 45° N are not related to blocking. The anomaly pattern of Fig. 4b is also different from the typical blocking anomaly pattern of Fig. 2b. It is dominated by a large positive anomaly centered at about 45° N and a negative anomaly north of it.

Summarizing, we have shown that whether or not a large positive anomaly in geopotential height is related to a blocking as defined by Rex depends very much on the latitudinal position of the anomaly center. A large positive anomaly centered at about 45° N represents a northward extension of the subtropical anticyclone. A large positive anomaly centred at about 60° N is accompanied with a negative anomaly at low latitudes and a blocking anticyclone centered at about 50° N. We

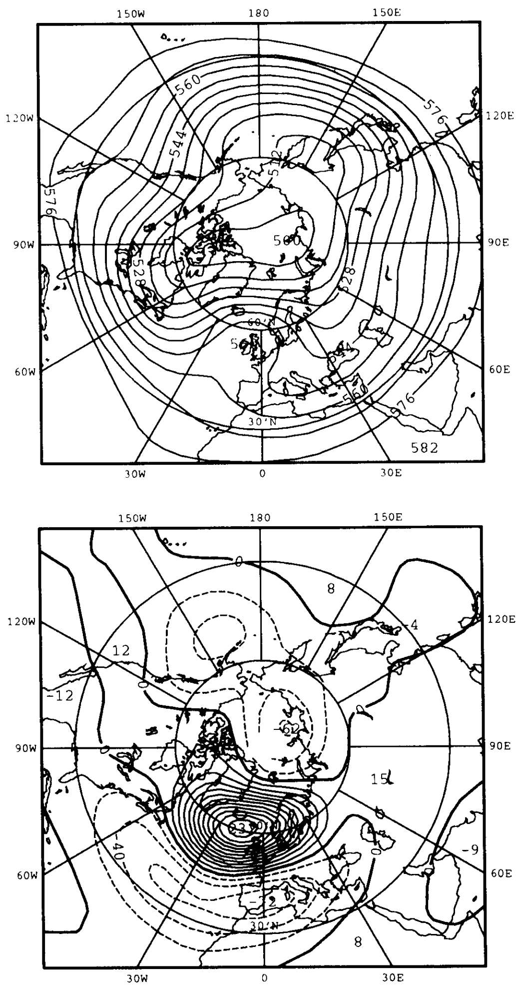


Fig. 2. The mean (a) and anomalies (b) of the 500 hPa geopotential height for the 200 days with the largest positive anomalous values of ZA60 (see text for more details). Contour interval is 80 m in (a) and 20 m in (b).

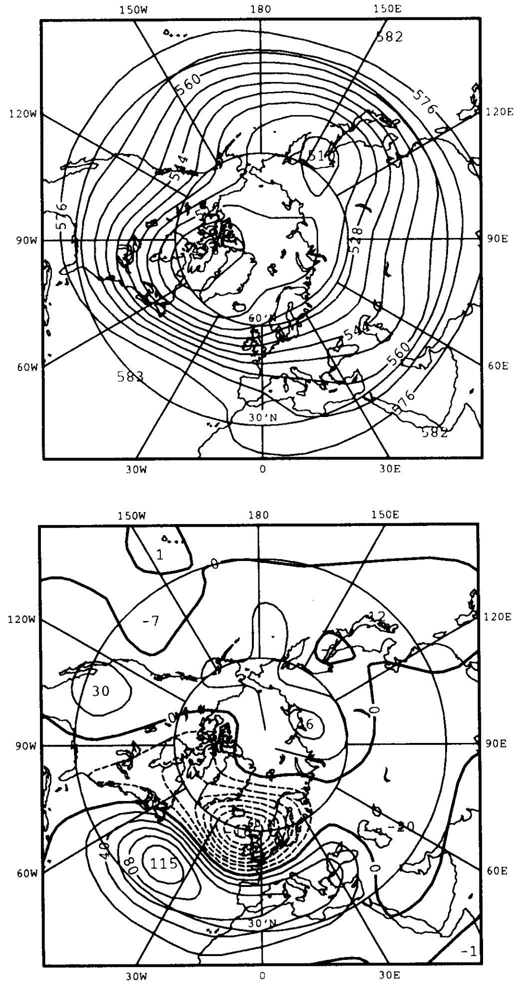
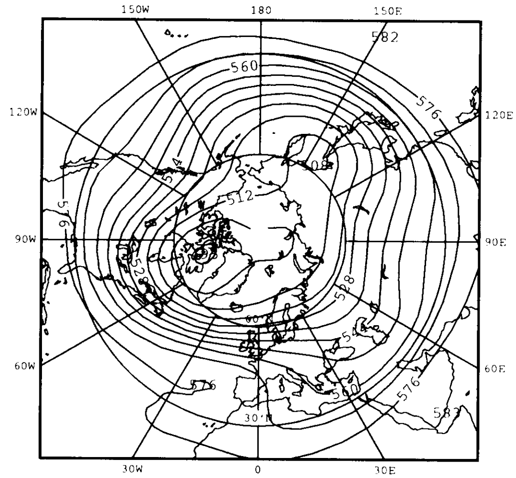


Fig. 3. As in Fig. 2 except for the 200 days with the largest positive anomalous values of ZA30.

may therefore conclude that we can not simply define a blocking at a particular grid point to be an anomaly at that point greater than some threshold values.

4. The day-to-day changes in geopotential height associated with blocking and strong zonal flow

As mentioned in the introduction, Horel (1985) has computed the day-to-day changes in positive geopotential height anomalies over the central Pacific and interpreted them as the day-to-day changes in the amplitude of the blocking pattern. In this section, the day-to-day changes in geopotential height associated with blocking are computed and the relevance of these day-to-day changes to the persistence of the blocking pattern is examined. For comparison, the day-to-day changes associated with strong zonal flow are also computed. If the daily 500 hPa geopotential height is indicated by $z(x, t)$, where x indicates a particular grid point and t a particular day, then the



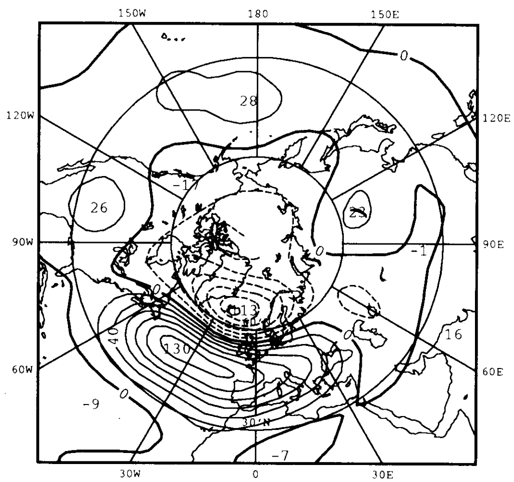


Fig. 4. As in Fig. 2 except for the 200 days with the largest positive anomalous values of ZA45.

day-to-day change of the 500 hPa geopotential height at that particular day is determined by

$$D(x, t) = |z(x, t+1) - z(x, t)|.$$

The day-to-day changes have been computed at each grid point for each day of the 10 winters. The climatological mean of D is computed by averaging the $D(x, t)$ over the dataset. The day-to-day changes associated with blocking are computed by averaging the $D(x, t)$ over the 200 days with the largest positive anomalous values of the time series

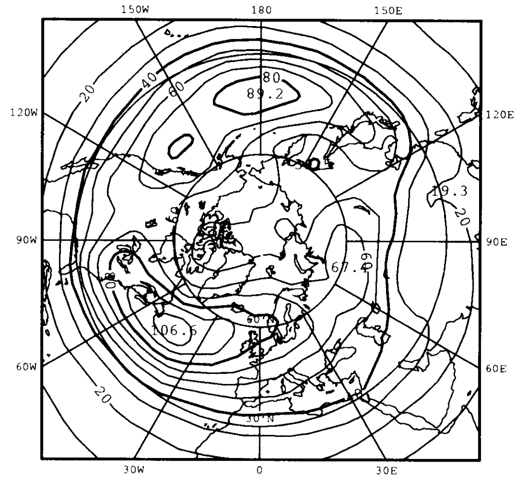


Fig. 5. The climatological mean day-to-day changes in geopotential heights at 500 hPa. Contour interval is 10 m.

ZA60. The day-to-day changes associated with strong zonal flow are computed by averaging the $D(x, t)$ over the 200 days with the largest positive anomalous values of ZA30. Computations have also been done with a few other blocking and strong zonal flow criteria (for example, ZA60 $\geqslant$ 100 m as a blocking criterion and ZA60 $\leqslant -100$ m as a strong zonal flow criterion). As long as the day-to-day changes in geopotential height are considered, the result is almost the same. The day-to-day changes are computed using the unfiltered daily 500 hPa geopotential height data. So both the high and the low-frequency disturbances are contributing to the changes. Computations have also been done using band-pass (2 to 6 days) and low-pass ($\geqslant$ 1 week) filtered data. We will discuss those results later in this section.

Fig. 5 shows the climatological mean day-to-day changes in geopotential height for the 10 winter seasons. It is dominated by maxima in the North Pacific and North Atlantic. A relatively weak maximum over north-central Russia is also observed.

Fig. 6a, b shows the day-to-day changes associated with the Atlantic blocking and the difference of this field with the climatological mean. Fig. 6a has approximately the same structure as the climatological mean (Fig. 5). However, the Atlantic maximum has shifted northeastwards to the north of the blocking high, leading to smaller

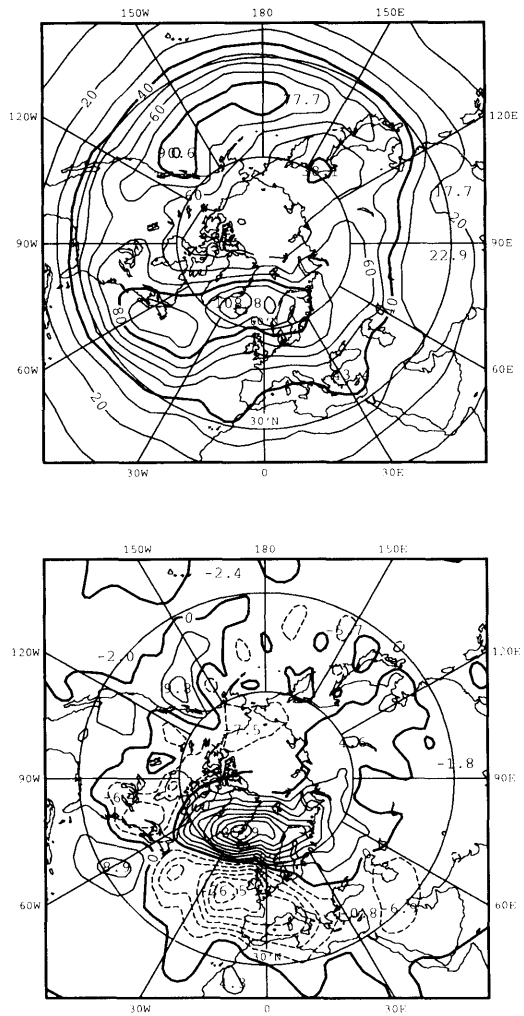


Fig. 6. The mean (a) and anomalies (b) of the day-to-day changes in geopotential heights associated with the North Atlantic blocking. Contour interval is 10 m in (a) and 4 m in (b).

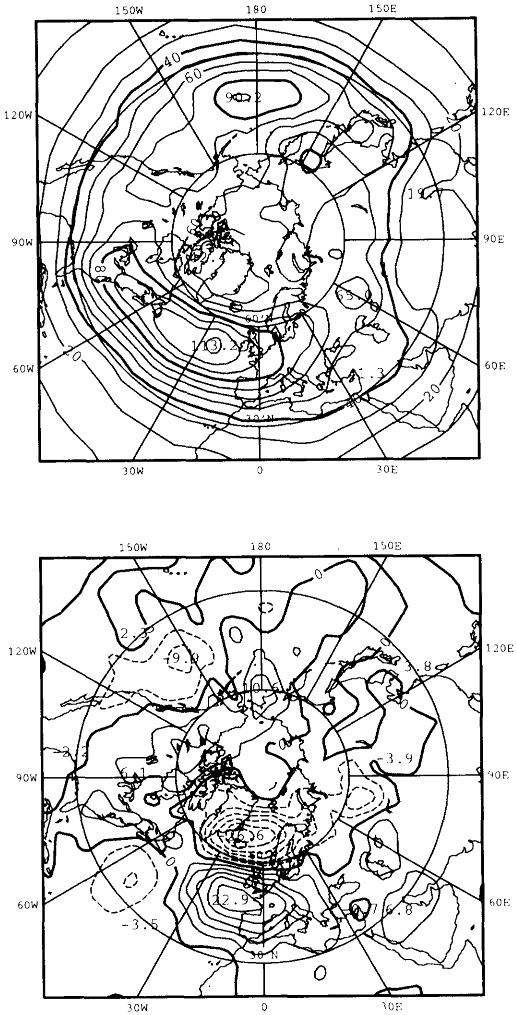


Fig. 7. The mean (a) and anomalies (b) of the day-to-day changes in geopotential heights associated with the North Atlantic strong zonal flow. Contour interval is 10 m in (a) and 4 m in (b).

than normal day-to-day changes over the blocking area and larger than normal day-to-day changes north of it. This can be clearly seen from the anomaly pattern (Fig. 6b). This result indicates that it is the shift in transient eddy activity resulting from the shift in the position of the jet that is mainly responsible for anomalies in daily variability of geopotential height during a blocking episode. To further confirm this result, the day-to-day changes in geopotential height have been computed with the band-pass (2 to 6 days) and low-pass ($\geqslant 1$ week) filtered data. They all show the same mean and anomaly patterns as Fig. 6a, b. However, the magnitude of the mean and anomalies computed with the band-pass filtered data is much larger than that computed with the low-pass filtered data. We may therefore conclude that the anomalous day-to-day changes in geopotential height during blocking episodes are mainly caused by anomalies in the high-frequency transient eddies. It is less clear how to get information on the persistence of the blocking regime itself from the day-to-day changes in geopotential height.

We find that smaller than normal day-to-day changes occur over the area where the blocking anticyclone is located and not over the area with the maximum positive geopotential height anomalies. Actually, the center of the positive anomaly at about 60° N separates the area with larger than normal day-to-day changes north of it from the area with smaller than normal day-to-day changes south of it. It is clear that the strength of the day-to-day changes depends very much on the exact latitude (relative to the center of the anomaly) where the changes are computed. North of the positive anomaly center the westerlies are stronger than normal and consequently there appears to be enhanced variability caused by the effect of transient eddies. South of the anomaly center, the reverse is true. This can explain the controversial results of Horel (1985) and Madden and Lejenäs (1989). Madden and Lejenäs (1989) have examined the day-to-day changes in geopotential height over the northeastern Atlantic and western European areas. They show that smaller day-to-day changes over western Europe are associated with low zonal index over the northeastern Atlantic. In contrast, Horel (1985) shows that large positive geopotential height anomalies over the central Pacific tend to exhibit larger day-to-day changes than the corresponding negative anomalies. Our result indicates that the controversial results of Horel (1985) and Madden and Lejenäs (1989) can be simply explained from the difference in the exact location where the day-to-day changes are computed.

Fig. 7a, b shows the day-to-day changes associated with strong zonal flow and their anomalies from the climatological mean. The day-to-day changes are stronger than normal over the area south of 60° N and weaker than normal north of 60° N. The anomaly pattern of Fig. 7b is very similar to the anomaly pattern associated with the blocking regime, but with opposite sign. Similar to the blocking case, the larger than normal day-to-day changes are associeted with enhanced westerlies and larger than normal transient eddy activity and the smaller day-to-day changes are associated with weakened westerlies and smaller than normal transient eddy activity.

In summary, we have shown that the anomalous day-to-day changes associated with the blocking regime are mainly caused by the northward shift of the jet stream and the corresponding shift in the track of the transient weather disturbances. The strength of the day-to-day changes depends very much on the exact latitudinal position where the changes are computed. This is in agreement with Blackmon et al. (1986) and Dole (1986a). They show that the activity of the transient weather disturbances is weakened near the center of the blocking high and enhanced north of it. Our study indicates that the day-to-day changes in geopotential height do not contain information about the persistence of the blocking pattern, but merely about the shift of the transient eddies caused by the blocking pattern. So we can not simply interpret the persistence of blocking in terms of the day-to-day changes in positive anomalies.

5. The duration of the blocking and strong zonal flow regimes

We have shown in the last section that the daily geopotential height changes near the center of the blocking high are small. However, small changes in geopotential height are not trivially connected to a large persistence of the blocking regime itself. Large-scale strong zonal flow may also persist for a long time independent of the fact that the strong westerlies cause large day-to-day changes within the zonal regime. In order to study the persistent character of blocking and strong zonal flow, we must distinguish the daily variabilities due to the transient weather disturbances from the degree of persistence of the flow regimes themselves.

In this section, persistence of blocking and strong zonal flow is expressed in terms of the duration of the corresponding anomaly patterns. As blocking and strong zonal flow regimes over the North Atlantic and western European areas are associated with approximately the same anomaly pattern with opposite sign, a single blocking index is used to measure the resemblance of a particular circulation pattern with the blocking regime or the strong zonal flow regime. To do this, each of the daily 500 hPa geopotential height anomaly fields is projected onto the blocking anomaly pattern of Fig. 2b. The projection area is the Atlantic-European area from 10° N to 85° N and from

90° W to 60° E. We call it the blocking index (BINX). It is defined as:

$$\text{BINX} = \frac{\langle z_b, z_d \rangle}{\langle z_b, z_b \rangle}$$

where z_b is the blocking anomaly field in geopotential height and z_d the daily geopotential height anomaly field. The angle brackets denote a squared norm inner product. A large positive blocking index represents a blocking pattern and a large negative blocking index is related to a strong zonal flow.

In order to study the persistent character of the blocking regime, consecutive days for which the blocking index exceeds a pre-selected threshold value are counted for the 10 winter seasons. Økland and Lejenäs (1987) have developed a convenient index to compute the climatological probability that a particular blocking event lasts at least i days:

$$S_i = \frac{\sum_{k=i}^{N} n_k}{\sum_{k=1}^{N} n_k} = \frac{\sum_{k=i}^{N} n_k}{N},$$

where n_k is the number of the blocking events lasting for k days. N is the total number of blocking events. The probability that the strong zonal flow regime lasts at least i days has also been computed. Fig. 8 shows, for the blocking index threshold value of 0.5 (BINX $\geqslant 0.5$ as a blocking criterion and BINX $\leqslant -0.5$ as a strong zonal flow criterion), the S_i for the blocking and strong zonal flow regimes. Closed circles are for the blocking regime and open circles for the strong zonal flow regime. The full (dashed) line is the 5 points running mean for blocking (strong zonal flow). Fig. 8 displays no significant differences between the persistence of blocking and strong zonal flow.

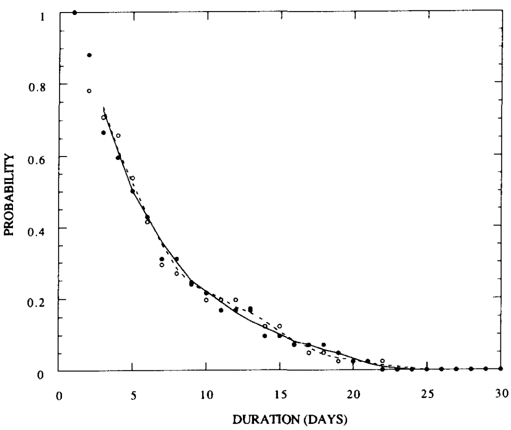


Fig. 8. The probabilities S_i that blocking (BINX $\geqslant 0.5$) and strong zonal flow (BINX $\leqslant -0.5$) events last at least i days. Closed circles are for blocking and open circles for strong zonal flow. The full (dashed) line is the 5 points running mean for blocking (strong zonal flow).

The analysis has been repeated using a few other blocking index threshold values. The result appeared to be insensitive to the exact values of the threshold. This can be clearly seen from Table 1. Table 1 gives, for blocking index threshold values of 0.5, 0.6, 0.7 and 0.8, the total number of blocking and strong zonal flow events in the 10 winter seasons and their average durations. For all the blocking index threshold values, we have found approximately the same number of blocking and strong zonal flow events and the average duration of the blocking and strong zonal flow events is almost the same. The probabilities S_i for the blocking and strong zonal flow regimes have also been computed using a dataset that has been smoothed by applying a 5-day running mean smoother. With respect to the relative persistence of blocking and

Table 1. *The total number of blocking and strong zonal flow (SZF) events in the 10 winter seasons and their mean durations in days; they are computed using BINX $\geqslant$ 0.5 (or 0.6, 0.7, 0.8) as a blocking criterion and BINX $\leqslant -0.5$ (or -0.6, -0.7, -0.8) as a strong zonal flow criterion*

	Number of blocking events	Mean duration of blocking	Number of SZF events	Mean duration of SZF
$\lvert\text{BINX}\rvert \geqslant 0.5$	42	6.1	41	6.2
$\lvert\text{BINX}\rvert \geqslant 0.6$	39	5.7	38	5.8
$\lvert\text{BINX}\rvert \geqslant 0.7$	38	4.9	36	4.9
$\lvert\text{BINX}\rvert \geqslant 0.8$	35	4.5	33	4.5

strong zonal flow, the result is qualitatively the same as the result for the unsmoothed dataset. Our results indicate that the blocking regime is not more persistent than the strong zonal flow regime.

The persistence of blocking has been compared with a first-order Markov process. Following Økland and Lejenäs (1987), the S_i of a first-order Markov process is determined as:

$$S_i = p^{i-1},$$

where p is a constant which is computed from the mean duration (D) of the blocking events:

$$p = 1 - \frac{1}{D}.$$

Fig. 9 shows, for the blocking index threshold value of 0.5, the S_i for blocking and the first-order Markov process. In this case, D equals to 6.1 and p equals to 0.84. It shows that the persistence of blocking does not exceed significantly the persistence expected by a first-order Markov process. This is in agreement with Økland and Lejenäs (1987). The S_i for blocking and the first-order Markov process have also been computed using different blocking index thresholds. Generally speaking, we find no significant differences in persistence between the blocking regime and the first-order Markov process. The persistent character of strong zonal flow has also been compared with the corresponding first-order Markov process. The differences between them are small (not shown).

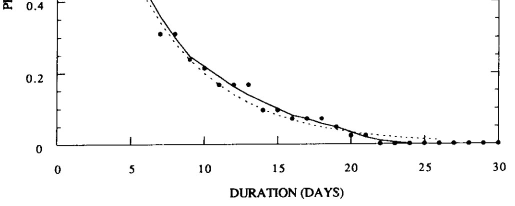


Fig. 9. The S_i for blocking (BINX $\geqslant$ 0.5) and a first-order Markov process. Closed circles are for blocking and the full line is the 5 points running mean. The dashed line is the expected probabilities if the statistics are modelled as a first-order Markov process.

Our result that blocking is not more persistent than strong zonal flow appears, at first, to be in contrast with a few other studies (Dole and Gordon, 1983; Blackmon et al., 1986). Dole and Gordon (1983) and Blackmon et al. (1986) have examined the persistence of blocking in terms of the duration of large positive anomalies at about 50° N. They show that on the average, large positive anomalies at about 50° N have a longer lifetime than the corresponding negative anomalies. However, as we have shown in Section 3, for the blocking and strong zonal flow anomaly patterns (Figs. 2b, 3b), positive anomalies at about 50° N are located over the blocking anticyclone center with less transient eddy activity and negative anomalies at about 50° N are associated with a stronger jet stream and more transient eddy activity. So at 50° N the negative anomalies are more likely to experience brief transient interruptions than the positive anomalies. This may account for the discrepancy between our result and the results of Dole and Gordon (1983) and Blackmon et al. (1986). This hypothesis is confirmed by looking more closely at the results of Dole and Gordon (1983). Dole and Gordon (1983) show that whereas for the unfiltered data the number of persistent positive cases (+100 m, 10 days) exceeds the number of persistent negative cases (−100 m, 10 days), for the low-pass filtered data the numbers of positive and negative cases are comparable. Actually, Fig. 6 of Dole and Gordon (1983) even shows that both in the Atlantic and Pacific areas, the number of persistent negative cases slightly exceeds the number of persistent positive cases. This result shows that although strong zonal flow exhibits more brief transient interruptions than blocking, the duration of the zonal flow regime itself is not shorter than the blocking regime. Our results confirm this.

6. Conclusions and discussion

In this paper, we have considered two problems relating to atmospheric blocking. The first problem is that of defining a blocking flow. The objective blocking criteria of Dole (1978) have been compared with the subjective blocking criteria established by Rex (1950a, b). Our study indicates that if we want to relate positive geopotential height anomalies to blocking as defined by Rex, not only the amplitude, but also the latitudinal position of the anomalies is important. Positive anomalies centered at about 45° N represent a northward extension of the subtropical anticyclone. Only for positive anomalies centered at about 60° N the objective criteria of Dole correspond to the blocking definition of Rex. Large positive anomalies centered at about 60° N are accompanied with negative anomalies at low latitudes and blocking anticyclones centered at about 50° N. Those results indicate that we can not simply define a blocking at a particular grid point to be an anomaly at that point greater than some threshold values.

We found that strong zonal flows over the North Atlantic are associated with a negative geopotential height anomaly centered at about 60° N and a positive anomaly south of it. Clearly blocking and strong zonal flow regimes have the same anomaly pattern but with opposite sign. This agrees with Dole (1986a).

The day-to-day changes in geopotential height associated with blocking are computed and the relevance of these day-to-day changes to the persistence of the blocking pattern is examined. We find that the day-to-day changes are smaller than normal over the blocking area, but larger than normal north of it. The anomalous day-to-day changes are mainly caused by the northward shift of the jet stream and the corresponding shift in the track of the transient weather disturbances. Hence, the day-to-day changes in geopotential height do not contain information about the persistence of the blocking pattern, but merely about the shift of the transient eddies caused by the blocking pattern. The strength of the day-to-day changes depends very much on the exact latitude (relative to the center of the anomaly) where the changes are computed. North of the positive anomaly center the westerlies are stronger than normal and consequently there appears to be enhanced variability caused by the effect of transient eddies. South of the anomaly center, the reverse is true. This explains the controversial results of Horel (1985) and Madden and Lejenäs (1989). We may therefore conclude that we can not simply interpret the persistence of blocking in terms of the day-to-day changes in positive anomalies.

The persistence of blocking and strong zonal flow has been examined. As blocking and strong zonal flow are associated with approximately the same anomaly pattern but with opposite sign, the persistence of blocking and strong zonal flow can be expressed in terms of the duration of the corresponding anomaly patterns. We have shown that the average duration of the blocking and strong zonal flow patterns is approximately the same. This leads us to conclude that although the daily changes in geopotential height are small near the center of the blocking high, the blocking regime itself is not more persistent than the strong zonal flow regime. The persistence of blocking and strong zonal flow has also been compared with a first-order Markov process. Generally speaking, we find no significant differences in persistence between the blocking and strong zonal flow regimes and the first-order Markov process.

Nigam and Lindzen (1989) and Da Silva and Lindzen (1993) suggested that blocking and strong zonal flows are simply associated with the amplifications or attenuations of the stationary planetary-scale waves. Using a linear primitive equation stationary wave model, they showed that stationary waves at middle and high latitudes are sensitive to small shifts in the subtropical jet. An equatorward shift increases and a poleward shift decreases the amplitude of the stationary waves. They suggested that these shifts can explain the generation of persistent large-scale anomalies in the extra-tropics. Tibaldi and Molteni (1990) examined the skill of the ECMWF model in forecasting atmospheric blocking. They showed that blocking frequency is severely underestimated in medium-range forecasts. They found that the inability of the model to simulate blocking is associated with its inability to amplify stationary waves. We have shown that blocking and strong zonal flow regimes have the same anomaly pattern but with opposite sign. The blocking pattern of Fig. 2a indeed appears to be an enhancement of the climatological winter mean pattern. This supports the conclusions of the above mentioned papers.

In order to properly interpret the persistence of blocking, we must emphasize that persistence ought to mean long lasting as compared to the time scales expected for transients of the same geographical scale. There is no doubt that blocking tends to persist longer than the much smaller scaled synoptic disturbances (Rex, 1950a, b; Dole and Gordon, 1983; Dole, 1986a, b). However, this comparison can be misleading in view of the dissimilar scales. Lindzen (1986) suggested that the relevant transients are the planetary-scale free Rossby waves. In that case, he found that the blocking regime is not unusually persistent. Our result that blocking is not more persistent than strong zonal flow and a first-order Markov process supports his argument.

To further clarify the picture of the persistence of blocking, it is also important to distinguish the variability caused by the transient weather systems within the blocking periods from the variations of the blocking regime itself. Blocking and strong zonal flow are typical large-scale, low-frequency circulation features with a characteristic time scale larger than the synoptic time scale. Both of them have significant effects on the high-frequency transient weather systems. We find that the variability caused by the transient weather systems is reduced near the blocking center. This is in agreement with meteorological experience that during blocking periods weather is rather constant from day to day and may be the same day after day for a few weeks. However, we must emphasize that a reduced variability of the daily transient weather systems near the blocking center does not necessarily mean a large persistence of the blocking regime itself. It only reflects the effect of the large-scale low-frequency blocking anomaly pattern on the high-frequency transient weather disturbances. We have shown that the strong zonal flow regime can persist as long as the blocking regime independent of the fact that the strong westerlies cause a large transient eddy activity within the zonal regime.

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