Aspects of a Northern Hemisphere Atmospheric Blocking Climatology

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ABSTRACT

A comprehensive climatology of Northern Hemisphere blocking is described based on a PV-θ wave-breaking index at the latitude of the climatological storm track and using the 40-yr ECMWF Re-Analysis (ERA-40) dataset. The general characterization of blocking regions is in agreement with most other studies, though more detail is provided here. In the annual average, blocking is most prevalent in the large region from the eastern Atlantic Ocean through Europe to central Asia with a secondary region in the central and eastern Pacific Ocean. Using a blocking criterion with the requirement for both longitudinal extent and temporal persistence, the peak in the frequency is in the Scandinavian region, where 24% of the days are characterized by blocking. In the east Pacific maximum, the corresponding number is 7%. However, there is considerable and very important interannual variability. The decay rate in the number of blocking events lasting at least a specified number of days is significantly less over Europe than elsewhere. However, the average intensity of blocking episodes is slightly higher in the east Pacific. The mean annual cycle of blocking is quite complex. Over most of Europe it continues through the year, with maximum intensities in the autumn and winter. To both the east and west, over the western Atlantic and Asia, there are two periods in the year of highest blocking frequency. Similar two-cycle behavior is found in the eastern Pacific region. The relationship of blocking with the storm track and the mean planetary-scale geopotential ridges is considered, and the evidence that blocking is a particular phenomenon with its own nonlinear dynamics is discussed.

1. Introduction and background

Atmospheric blocking is a prominent feature of the midlatitude low-frequency atmospheric variability associated with the breakdown of the “high kinetic energy level” state of the atmosphere, which is characterized by strong westerly flow, into a “low kinetic energy level” state. The onset of blocking obstructs the easterly advance of weather systems, and the midlatitude westerly flow can even be replaced locally by an easterly flow. A more cellular circulation pattern prevails, and the flow exhibits a significant meridional component (Rex 1950a). Blocking has a barotropic signature (Rex 1950a; Green 1977), which includes a surface anticyclone located below an upper-level quasi-stationary warm ridge or cutoff anticyclone developing on the poleward side and often a cold trough or cutoff cyclone on the equatorward side. During the winter, blocking can bring spells of extremely cold weather (e.g., Hoskins and Sardeshmukh 1987), while during the summer blocking is sometimes related to severe droughts and heat waves (e.g., Green 1977; Black et al. 2004).

The first attempt to identify the synoptic characteristics of blocking was presented by Namias (1947) in his investigation of the evolution of the Northern Hemisphere circulation anomalies during the abnormal winter of 1947/48. Berggen et al. (1949) conducted a more in-depth study of the horizontal and vertical structures of the thermal and wind fields during the European blocking event of February 1948. Elliott and Smith (1949) gave a subjective catalog of blocking cases based upon the requirement that a persistent high must be identified in the latitude band 55°–60°N. The seminal study by Rex (1950a) proposed a set of criteria for the identification of blocking. The westerly flow must split into two distinct branches, which encompass the blocking anticyclone, with each branch transporting appreciable atmospheric mass. This double-jet structure must extend for at least 45° of longitude and the storm track should be split in a similar manner. Also, there must be a sharp transition from zonal flow upstream to cellular

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flow downstream of the jet split. Finally, the above pattern must persist for at least 10 days.

Despite the importance of blocking in many midlatitude regions, a complete theory accounting for the dynamics of blocking onset, maintenance, and lysis is still lacking. Rex (1950b) proposed the hydraulic jump as a mechanism that could account for the breakdown of the westerly flow and the development of a large-scale blocking-like vortex. This analog was challenged by Egger (1978) on the grounds of the argument that the turbulent nature of the hydraulic jump cannot be associated with the stability of a blocking anticyclone. Namias (1950) and White and Clark (1975) proposed that a blocking formation is a manifestation of baroclinic instability through the discharge of cold air that had been trapped in the polar cap because of the presence of strong midlatitude westerlies. Green (1977) emphasized the role of transient fluxes in the maintenance of the persistent European blocking anticyclone of July 1976.

Several more recent blocking theories were proposed that could be classified into two major categories (see also Tyrlis 2005). The first category is that of global theories, which emphasizes the influence of processes occurring on large or even planetary scales. Some of the global theories explain blocking through the participation of large-scale waves, either stationary or traveling, at some stage of the blocking development (Grose and Hoskins 1979; Austin 1980; Hansen and Sutera 1993). Others associate the planetary waves with Rossby wave trains forced by tropical convection resulting in blocking-like anomalies in the midlatitudes (Hoskins and Karoly 1981; Hoskins and Sardeshmukh 1987; Ferranti et al. 1994). Also, there are global theories that consider blocking to be a subresonant equilibrium state associated with the interaction between a zonal flow and topography in a channel model (e.g., Charney and DeVore 1979). The second category of blocking theories emphasizes the importance of the local processes. There are local equilibrium theories (e.g., Pierrehumbert and Malguzzi 1984), in which the equilibrium solutions are sought in the locality of the blocking. Modon theories belong to the second class of local blocking theories (McWilliams 1980). Local processes are also paramount in the studies in which the role of synoptic transients is highlighted (e.g., Austin 1980; Shutts 1983, 1986). More recent studies provided evidence of enhanced transient activity prior to the onset of blocking (Nakamura and Wallace 1990, 1993; Nakamura et al. 1997), while Sanders and Gyakum (1980) and Colucci (1985, 1987) concluded that explosive cyclogenesis is a vital source of vorticity that can perturb the planetary wave environment and result in subsequent downstream blocking.

The lack of understanding of blocking is illustrated by the variety of methods utilized for its identification. Some of the methods for the identification of blocking as a weather regime are statistically based. Algorithms that look for blocking regimes have used hierarchical methods (Cheng and Wallace 1993), nonhierarchical or partitioning methods (Michelangeli et al. 1995), methods that look for local maxima in the atmospheric state probability distribution function (PDF; Kimoto and Ghil 1993a,b; Corti et al. 1999), mixture model methods (Smyth et al. 1999), and nonlinear equilibrium methods (Vautard 1990). The preprocessing of data or the tuning of parameters in the algorithms employed by each technique is always a source of arbitrariness. Other methods use a variety of techniques based on measures of the strength of the westerly flow (e.g., Lejenas and Okland 1983; Tibaldi and Molteni 1990; Pelly and Hoskins 2003), or on the identification of persistent positive height anomalies (Dole and Gordon 1983; Dole 1986). With all of the methods, some arbitrariness is introduced as synoptic knowledge is used for the calibration of the criteria for blocking identification. For example, Tibaldi and Molteni (1990) applied a combination of subjective thresholds in their measures of reversals in meridional geopotential gradients. Dole and Gordon (1983) imposed thresholds for the amplitude and persistence of positive height anomalies.

In this study, we present the main aspects of a Northern Hemisphere blocking climatology compiled with the aid of the potential vorticity (PV)–potential temperature (θ) blocking index developed by Pelly and Hoskins (2003, hereafter PH). In section 2 the methodology followed for the identification of blocking and the dataset used are briefly described. In section 3 the climatology of the blocking index itself is presented. Section 4 gives the climatology of blocking frequency and section 5 investigates aspects of its duration and intensity. Some concluding comments are presented in section 6.

2. Methodology and data description

a. Methodology

1) The index Ψ

The PV–θ index (Ψ) used to determine blocking is related to the strength of the westerly flow and, conceptually, it is close to the definitions provided by Lejenas and Okland (1983) and Tibaldi and Molteni (1990). However, it exploits the power of PV–θ theory
(which can itself be viewed as a basis for many of the
blocking theories), and it is a macroscale measure of the
meridional gradient of $\theta$ on the 2-PVU surface [1 PV
unit (PVU) = $10^{-6}$ m$^2$ s$^{-1}$ K kg$^{-1}$], rather than the
geopotential height on the 500-hPa surface. The invert-
ibility principle (Hoskins et al. 1985) suggests that a
reversal in the usual equatorward increase in $\theta$ is likely
to be associated with a reversal or weakening in the
westerly flow.

Because the interference with the eastward move-
ment of weather systems is considered to be an essen-
tial aspect of blocking, at each longitude the reversal is
looked for in the neighborhood of a central blocking
latitude (CBL) determined as the location of the maxi-
mum in latitude of the 300-hPa synoptic time-scale
transient eddy kinetic energy. Here, as in PH, the CBL
will be a smoothed version of this latitude computed
using data from the 15-yr European Centre for Me-
dium-Range Weather Forecasts (ECMWF) Re-
Analysis (ERA-15) and shown in Fig. 1. Also shown are
unsmoothed versions of this latitude derived using ERA-40
data for the annual mean (blue) and the four seasons.

Referring to the example of a blocking event over
Europe depicted in Fig. 2, the average value of $\theta$ on the
2-PVU surface in the 15° latitude $\times$ 5° longitude box
equatorward of the CBL is subtracted from that in the
similar poleward box. As discussed above, the process
is repeated for central latitudes 4° to the north and
to the south, and $B$ at this longitude is defined to be the
maximum of the three values.

2) LOCAL AND INSTANTANOUS BLOCKING

When $B$ is positive at a certain longitude, then $\theta$ is on
average higher on the poleward side of the CBL region.
This will be taken as an indicator that blocking may be
occurring, and it is referred to as local and instantan-
eous blocking (LIB).

3) SECTOR BLOCKING

Since LIB will include synoptic-scale reversals in the
meridional $\theta$ gradient, it is desirable to introduce a mea-
sure based on a longitudinal extent similar to that of the
event depicted in Fig. 2. Sector blocking (SB) is said to
occur at a longitude when, in the 45° sector centered on
it, LIB is occurring in a continuous longitudinal region
of at least 15°. The 45° sector width compares with the
65° used by PH and this choice was determined by the
following factors. It should be larger than a Rossby
radius of deformation, which is a length scale for syn-
optic systems. However, it should not be so large as to

![Fig. 1. The longitudinal distribution of the CBL determined as a smoothed version of the latitude of the maximum in synoptic time-scale 300-hPa kinetic energy according to ERA-15 data (black). Also shown are the unsmoothed versions of this latitude derived using ERA-40 data for the annual mean (blue) and the four seasons.](image-url)
minimize the possibility that more than one large-scale blocking event could occur at the same time within the same sector.

4) SECTOR BLOCKING EPISODES

To also take into account the requirement for persistence, a sector blocking episode (SBE) is defined to occur when an SB event lasts for at least 5 days. In their work, PH used 4 days as a duration threshold, but a comparison with other studies (Trenberth and Mo 1985; Lupo and Smith 1995) and also the desire to ensure the inclusion of only greater than synoptic time scales suggested the larger threshold used here. Using the indices defined here, continuous information on SB or SBE occurrences, as well as blocking duration and intensity, can be obtained for “running sectors” covering the whole Northern Hemisphere at increments of 5° of longitude. It should be noted that in Berrisford et al. (2007) the word sector is dropped from both sector blocking and sector blocking episodes.

b. Data description

In this study, data are derived from the ECMWF ERA-40 dataset. ERA-40 is a second-generation reanalysis prepared with the objective of providing the best possible analysis of past observations, given the existence of an ever-changing global observation system, and using a state-of-the-art data assimilation and forecasting system. The ERA-40 project employed a 3D variational data assimilation system, used operationally at ECMWF between January 1996 and November 1997, in order to perform a synthesis of all of the available inhomogeneous in situ observations and remotely sensed measurements obtained for the period September 1957–August 2002 (Uppala et al. 2005). The original ERA-40 fields are archived in spectral T159 resolution or an N80 reduced-Gaussian grid, but in this study the fields were interpolated to an N80 full-Gaussian grid. Six-hourly fields of θ and wind components on the 2-PVU surface, MSLP, and also geopotential, streamfunction, and wind components on the 250-hPa surface have been used. In total, 44 winter periods were defined with the first period being the winter of 1957/58 and the last being the winter of 2000/01. Each winter period is labeled by the year of the corresponding January. Following the method described in the previous section, B has been calculated for the main synoptic hours and throughout the period 1 October 1957–31 December 2001. To remove some high-frequency noise, daily mean B values were calculated and used as a basis for the analysis of blocking. In this study winter corresponds to the period December–February (DJF), spring to the period March–May (MAM), summer to the period June–August (JAS), and autumn to the period September–November (SON).
3. Climatology of $\mathcal{B}$

Hovmöller plots showing the climatological annual cycles of the 250-hPa zonal wind, interpolated along the CBL, and $\mathcal{B}$ are given in Fig. 3. The weakening and northward migration of the Atlantic and Pacific jets during the summer are reflected in a weaker westerly flow at the CBL.

During the winter, the highest mean values of $\mathcal{B}$ are found over Europe and the eastern Atlantic Ocean, while during the summer high values are recorded over eastern Europe and central Asia (Fig. 3b). An isolated maximum occurs in the central Pacific during the second half of the boreal summer. Upstream of the Pacific jet entrance near 120°E there is a very sharp eastern limit in the high values of $\mathcal{B}$, while a less distinctive boundary is found upstream of the Atlantic jet entrance. The lowest values are found on the western sides of the Pacific and Atlantic basins, within the vicinity of the two jets, and especially in the western Pacific from mid-September to mid-December when the jet is very strong. The fact that the westerly wind and $\mathcal{B}$ profiles are near mirror images (the negative correlations between them are at least 0.8 for most longitudes) is consistent with the latter being an approximate inverse measure of the strength of the westerly flow.

Figure 4a shows the frequency distributions of winter $\mathcal{B}$ for three longitudes: 20°E (Europe), 230°E (eastern Pacific), and 270°E (North America). The three distributions are generally similar in shape but shifted in value. This shift is clearly important when the possibility of positive $\mathcal{B}$, and therefore LIB occurring, is being considered. However, in this regard, the shapes of the tails of the distributions are also important. It is clear that the positive tail for 20°E is enhanced, thus giving evidence that blocking here is more than just a random process. The mean of this distribution is about $-3$ and is therefore displaced from the mode ($-5$) by some 2 K, again reflecting the enhanced positive tail. In contrast, the negative tail is enhanced for 230°E, which is suggestive of an enhanced number of strong westerly flow events there. For 270°E, neither tail appears to be strongly enhanced.

To provide relevant information for all longitudes, the first three moments of the winter $\mathcal{B}$ distributions are shown in Fig. 4b. The profile of the mean is consistent with Fig. 3b and highlights the areas of higher mean values over Eurasia and the eastern Pacific. The standard deviation varies little with longitude, but the lower value there implies that the distributions are slightly more compact over Eurasia. The skewness is seen to be positive over Eurasia and negative over the central and eastern Pacific. This is consistent with the enhanced positive tail at 20°E, the negative tail at 230°E, and the negligible asymmetry at 270°E discussed above.

Following White (1980), Nakamura and Wallace (1991) found that the skewness of the 500-hPa geopotential height was largest in magnitude over the oceans, being positive north of the storm tracks and negative to the south. They found that the signal was dominated by contributions from time scales of 1 week to 1 month and interpreted it in terms of long-lived blocking highs to the north and cutoff lows to the south. Since both of these features would also correspond with large values of $\mathcal{B}$, one might have expected strongest positive skewness in it over the oceanic storm tracks. However, here the skewness in $\mathcal{B}$ has been found to be near zero over the Atlantic and negative over the Pacific, with the positive values being in the Eurasian region. An alternative hypothesis for the earlier results is that the skewness in 500-hPa geopotential height is due simply to latitudinal fluctuations in the position of the region of strongest gradients (T. J. Woollings 2007, personal communication).

4. Climatology of blocking frequency

a. Annual mean

Figure 5 gives the annual mean longitudinal profiles of the frequency of blocking as given by the three measures LIB (dotted), SB (dashed), and SBE (dashed-dotted). The three profiles are qualitatively similar. There is the expected increase from LIB to SB frequency as large-scale blocking can occur anywhere in the 45° wide sector centered on the longitude, and a decrease in SBE frequency because of the 5-day persistence requirement.

The areas of more frequent blocking occurrence in the Northern Hemisphere are in the regions of high mean $\mathcal{B}$ values seen in Fig. 3b. Abundant blocking is primarily found over an extensive area covering the eastern Atlantic, Europe, and much of Asia. A second blocking region is found in the Pacific extending from the central to the eastern parts of the oceanic basin. The highest frequency of blocking lies near Scandinavia (20°E), where about 30% of the days are characterized by LIB occurrence and 24% by SBE occurrence. Blocking activity in central Asia (80°E) appears in the form of a shoulder in the overall blocking frequency pattern with an SBE frequency of around 16%. SBE occurrence is much lower, about 7%, in the east Pacific maximum. Blocking is very infrequent over the western parts of the Atlantic and Pacific basins with an SBE frequency of about 2% there. The LIB profile is very...
Fig. 3. Hovmöller representation of the annual cycle along the CBL of (a) the 250-hPa zonal wind speed and (b) the index $\mathcal{B}$. The abscissa shows longitude (east). Tick marks on the ordinate denote the beginning of a month. The geographical regions used in this paper are indicated in (b).
similar to, but less noisy, than that produced by PH based on the shorter 5-yr period.

Assuming normal distributions for \( B \) at each longitude with the observed mean and standard deviation (or even a uniform value) gives a frequency curve for LIB that is very similar to that actually found. However, it should be noted that the mean values used in such a calculation are influenced by asymmetries in the tails of the actual distributions. As can be seen from Fig. 5, the ratio of SB to LIB is almost independent of longitude. This suggests that the spatial coherence of \( B \) does not have strong longitudinal variation. However, the ratio of SBE to SB, which reflects the temporal coherence of sector blocking, varies by a large amount.

Over Europe it is 0.6, implying that the majority of days that are days with SB are also days that are part of a long-lasting SBE, whereas over the Pacific blocking region it is 0.3 and over the jet regions it is down to 0.2.

The higher blocking occurrence in the Pacific, the Atlantic, and over Europe was also reported by some of the very first studies of blocking climatology, such as Elliott and Smith (1949) and Rex (1950b). Attention was not given to the existence of the third area of abundant blocking over central Asia, perhaps because of the sparsity of data in the region. Dole and Gordon (1983), who used threshold methods for the identification of persistent positive 500-hPa height anomalies, did discuss the occurrence of blocking on the lee side of the Ural Mountains. This feature was discussed also by some later studies, such as Tibaldi and Molteni (1990), Lupo and Smith (1995), and Wiedenmann et al. (2002).

The fact that the blocking regions—the eastern Atlantic–Europe, the Pacific, and also Asia—are ones with local maxima in the mean values of \( B \) is consistent through invertibility with the fact that they are also the regions of mean planetary-scale geopotential ridges on the northern flanks of the CBL. Blackmon (1976) and Blackmon et al. (1977) found that lower-frequency variability occurs downstream of the high-pass variability in the storm tracks. Consistent with this, the annual mean profile of the 250-hPa 2–6-day time-scale transient eddy kinetic energy (TEKE) interpolated along the CBL (indicated in Fig. 5) shows that in the annual average the blocking in the eastern Atlantic–European region occurs downstream of the maximum in transient activity. The spatial relationship in the Pacific is less clear but appears to be generally similar in the annual average.

Despite the general qualitative agreement on the main regions of blocking activity, there is considerable disagreement among studies over quantitative results. Here, the ratio of the peak in the Atlantic–European and Pacific SBE frequencies is about 3.4 (Fig. 5), which compares with the value of 2.7 reported by PH and also by Rex (1950b). However, Lupo and Smith (1995) and Wiedenmann et al. (2002) found that the Atlantic blocking frequency exceeds the Pacific frequency by factors of just 1.5 and 1.6, respectively. Dole and Gordon (1983) and Tibaldi and Molteni (1990) found that Atlantic and Pacific maxima of blocking frequency are almost equal. However, as has already been seen, the climatological mean state in the eastern Atlantic is much closer to being blocked than in the Pacific. When this mean state is removed, as in the 500-hPa height anomaly study by Dole and Gordon (1983), the frequency of blocking-like events in the Pacific and the Atlantic regions becomes equal. This is consistent with
the similar standard deviations in $B$ found in the two regions as discussed above and reconciles the differing results for the ratios in the Atlantic and Pacific blocking frequencies. As shown by PH, the large frequency of blocking in the Pacific reported by Tibaldi and Molteni (1990) is due to the use of a constant latitude for the calculation of their blocking index. When a storm-track-related latitude is used, the Atlantic–European peak in blocking frequency dominates as it does here.

b. Mean annual cycle

A Hovmöller representation of the mean annual cycle of the LIB frequency across the Northern Hemisphere is given in Fig. 6. The mean annual cycles of SB
and SBE (not shown) both exhibit behavior that is similar to this. With some exceptions that are discussed below, blocking across the Northern Hemisphere is generally more widespread during the extended winter period. The center of gravity of blocking in the Atlantic–European–Asian region tends to move westward in April, eastward in June, and somewhat westward again in September, thus making an e-like pattern in the figure. In the Pacific the movement of the center of gravity of blocking tends to be in the opposite direction, thus making a mirror-image pattern.

Associated with this behavior are differing seasonal cycles in various regions. In the western Atlantic (near 300°E), the blocking has an annual cycle with a maximum in the period January–April and a minimum in July–October. In the eastern Atlantic there is relatively more blocking activity in autumn and the minimum becomes a sharper one in July and August. Over most of Europe, blocking tends to occur throughout all of the year, but moving farther eastward there is a transition to a two-cycle pattern in eastern Europe and Asia (30°–100°E), with one maximum in January–March, well separated from another in July–August, and somewhat weaker values in the autumn.

Across the Pacific Ocean the annual cycle of blocking in most of the region (140°–210°E) is similar to that in eastern Europe and Asia, with peaks in January–March and July–August. The eastern Pacific region (220°–240°E) has the highest blocking activity across the oceanic basin, with a minimum in July–August and a tendency for maxima in the periods before and after this.

Any possible relationship between the annual cycles of blocking and storm-track activity, discussed above in the context of their annual averages, may be analyzed using Fig. 6, as this also includes contours of TEKE interpolated to the CBL. The two storm-track regions and the “midwinter suppression” in the Pacific storm track (Nakamura 1992; Christoph et al. 1997) are apparent. Eurasian blocking activity occurs downstream of the Atlantic TEKE maximum. It is evident that the longitude of the TEKE maximum also shows a two-cycle pattern with its most eastward location occurring in July and to a lesser extent in January. There are signs of a similar relationship in the eastern Pacific, where the upstream storm track and blocking are both weak in summer, strong in the preceding and following months, and exhibit smaller minima in midwinter. However, there is no such relationship in the central Pacific. Here, winter blocking is upstream of the storm track and late summer blocking is in the middle of an extended but weak storm-track maximum.

c. Interannual variability of blocking activity

The interannual variability of blocking over the 44-yr period is very large and qualitatively similar whichever index for blocking is used. As an example, Fig. 7 shows a Hovmöller diagram of the winter SBE frequency. There is no indication of a strong trend or of coherent
year-to-year variability. The winter of 1962/63 stands out as being rather different from the others, with significant Euro-Atlantic blocking occurring just west of the 0° meridian. This is consistent with the severity of this winter in western Europe. For example, it was the coldest winter in the United Kingdom since 1740 (Booth 1968; Shellard 1968). However, it is also clear that in this year blocking was very unusual in the Pacific, with anomalously high frequencies occurring in the western and central Pacific, again far to the west of the usual location. In the following year, 1963/64, the blocking was strong even farther west into the Atlantic.

5. Duration and intensity of blocking

a. Duration

The seasonal and annual mean longitudinal profiles of the duration of SBEs can be seen in Fig. 8. (It should be recalled that 5 days is the minimum duration for an SBE.) In the annual mean the longest SBEs are found in Europe (7.6–8.0 days), while those in the central and eastern Pacific typically last 6.5–6.8 days. The shorter duration here is in agreement with the results of Lupo and Smith (1995) and Wiedenmann et al. (2002).

The seasonal variability in blocking duration is generally small. The exceptions to this are the western and central Pacific and the western Atlantic, in which the winter period that has most frequent blocking also has events with the longest duration.

Following PH (and inspired by Dole and Gordon 1983), the temporal behavior of blocking events is summarized using histograms of the natural logarithm of the number of SB events that last at least a specified number of days. For the whole Northern Hemisphere such histograms are shown in Fig. 9a. This total number corresponds to the sum of events occurring in eight individual sectors that span the whole Northern Hemisphere. One sector is centered at 0° and the others are incremented by 45° of longitude and, thus, all of the prominent regions of Northern Hemisphere blocking are covered. The same diagram for Europe (20°E) is given in Fig. 9b. Over the whole Northern Hemisphere there is a 1 in 5.7 chance of an event that has lasted 1 day surviving to 5 days (an SBE), a 1 in 6.4 chance that it will then last from 5 to 10 days, and 1 in 4.9 chance...
that it will last from 10 to 15 days. The relative abundance of long-lasting events is shown by the fact that if the 1–5-day chance continued for the subsequent periods, the chance of an event at 1 day lasting to 15 days would be some 2.5 times lower than the actual 1 in 178. Over Europe the corresponding chances of surviving from 1 to 5 days, 5 to 10 days, and 10 to 15 days are all greater, 1 in 4.0, 1 in 4.3, and 1 in 3.5, respectively. Multiplying them together, the chance of surviving from 1 to 15 days is about 1 in 60, a factor of 3 larger than for the whole Northern Hemisphere. The differing ratios of the frequencies of SBE and SB days around the hemisphere noted above in the discussion of Fig. 5 are consistent with the analysis here.

As stated in Dole and Gordon (1983) and PH, for a first-order Markov process with the probability of an event that lasts \( n \) days surviving to \( n/12 \) days being independent of \( n \), then the logarithmic profiles would be fitted by straight lines whose slope would give the decay rate of the population of events. The discussion of Figs. 9a and 9b has highlighted that the longer-lasting event categories are more populated than this would suggest. As in PH, a somewhat better fit is given by two lines, one for synoptic time scales and the other with shallower slope at longer time scales.

Decay rates have been calculated for synoptic time scales, 1–3 days, and longer time scales using linear regression applied to such analyses for sectors around the Northern Hemisphere. To avoid noisy longitudinal profiles, the entry for each duration bin (e.g., Fig. 9a) has been spatially filtered by applying a running-average smoothing over a 45° wide sector. Figure 10 shows the seasonal and annual mean longitudinal profiles of the decay time scales (inverse decay rates) for synoptic time scales \( \tau_{1-3} \) (left panel) and longer time scales, \( \tau_{4-14} \) (middle panel), and their difference \( \tau_{4-14} - \tau_{1-3} \) (right panel). On synoptic time scales, the decay time scale is generally about 2 days. It does not vary greatly with season or longitude, though it is generally higher over Eurasia. The longer-time-scale event’s decay time scale has a similar longitudinal structure and tends to be larger in winter. The difference between them, a measure of the difference between the nature of the longer and synoptic time-scale events, is generally about 1/2 day in the Atlantic and Eurasian regions and somewhat smaller elsewhere, in particular in the Pacific blocking region. In winter the magnitude tends to be larger, close to 1 day, particularly in regions where winter blocking dominates. This “time-scale separation” can be interpreted as providing firm evidence for different dynamics-governing blocking episodes. It is smaller than that found by PH (who used a shorter climatology and blocking sectors of length 65°) but it is quite robust and is larger than that found by Berrisford et al. (2007) for the Southern Hemisphere.

b. Intensity

The intensity of blocking as measured by LIB can be taken to be the value of \( B \) at that location and time. However, for SB and SBE the choice is less clear. Among various methods for the calculation of a daily measure of SB intensity, the average of \( B \) corresponding to the consecutive grid points in which LIB occurs (at least three by definition) has been found to be representative of the actual intensity of the blocking event occurring in a part of the sector. The overall intensity of an SB or SBE event is taken to be the average of the individual daily SB intensities throughout the duration of the event. The annual mean longitudinal distribution of all the available blocking intensity measures can be found in Fig. 11a. As expected, the higher intensities are associated with SBEs, since the strongest events are more likely to be characterized by larger values of both size and duration, the two prerequisites for SBE occurrence. The LIB intensity is the lowest, since this category includes synoptic events, while the SB profile is the smoothest as it both contains more cases than SBE and has an inherent spatial smoothing in its definition.
as compared with LIB. The three measures of intensity give similar indications of the variation in the intensity of blocking events around the Northern Hemisphere, with peaks in the western European and eastern Pacific blocking regions. However, the relative magnitudes of these peaks vary with the measure. For LIB the average intensity is slightly greater in Europe whereas for SBE it is greater in the east Pacific.

The population distributions of SBE events with respect to SBE intensity at various longitudes (Fig. 11b) provide more information for these longitudes than do the mean values given in Fig. 11a. As was the case for distributions presented by Wiedenmann et al. (2002), they are positively skewed resembling the distributions of other positive quantities such as precipitation (Wilks 1995; Jolliffe and Stephenson 2003). In the four sectors shown, the lowest distribution mode is over Asia, followed by Europe, and the highest value is over the eastern Pacific.

From these panels, it is seen that the blocking events that occur over the eastern Pacific are the most intense in the Northern Hemisphere, and that those in Europe and especially over Asia are notably weaker. This result is somewhat unexpected given the distributions of $B$ shown above in Fig. 4a, and is one that would not be given by a first-order Markov model. However, it is in line with previous climatologies of blocking intensity (e.g., Wiedernmann et al. 2002), except that of Lupo and Smith (1995) whose 3-yr climatology included only a sample of 63 events.

The annual cycle in the mean monthly SB intensity, which is preferred because of its smoothness, is shown in Fig. 11c. In general blocking is most intense in the autumn. In Europe the maximum intensity period extends through the winter. In the eastern Pacific, as was the case for the frequency of blocking (Fig. 6), there is a secondary maximum in the April–May period in addition to the autumn maximum.

6. Some concluding comments

In this paper a comprehensive climatology of blocking as seen in the 44 yr of the ERA-40 reanalysis has been given. The measures of blocking are based on an index $B$ of the difference between $\theta$ on the dynamical tropopause (PV2 surface) to the north and south of a central blocking latitude (CBL). The latter varies with longitude but is kept constant with time, although it is
allowed a variation of 4° of latitude. When $B$ is positive, there is a large meridional-scale reversal of the usual equatorward gradient in $\theta$ and local instantaneous blocking (LIB) is diagnosed. Sector blocking (SB) introduces a 15° longitude criterion and sector blocking episodes (SBEs) an additional 5-day duration criterion. SBEs can be considered full blocking events.

The general characterization of Northern Hemisphere blocking regions is in agreement with most other studies, though more detail is provided here. In the annual average, blocking is most prevalent in the large region from the eastern Atlantic through Europe to central Asia with a secondary region in the central and eastern Pacific. Near Scandinavia about 24% of days are contained in SBEs whereas the eastern Pacific maximum is about 7%. However, there is considerable and very important interannual variability. The decay rate in the number of SB events lasting at least a specified number of days is significantly less over Europe than elsewhere. However, the average intensity of the SBEs is slightly higher in the eastern Pacific.

The mean annual cycle of blocking is quite complex. Over most of Europe it continues through the year, with maximum intensities in the autumn and winter. To both the east and west, over the western Atlantic and Asia, there are two periods in the year of highest blocking frequency. A similar two-cycle pattern of behavior is found in the eastern Pacific region.

Consistent with many studies suggesting the important role played by the storm-track transients, blocking in the European region appears to occur at the end of the Atlantic storm track, following its longitudinal movement in the annual cycle. This also appears to be the case, though to a lesser extent in the eastern Pacific, but not in the central Pacific.

A relationship that is more striking and applies for variation with both longitude and time of year is the correlation between blocking frequencies and the mean value of $B$. The latter is itself strongly inversely correlated with the strength of the mean westerly flow at the CBL. At its simplest level, this is in agreement with the frequently made observation that the blocking high regions are those of the mean planetary-scale geopotential ridges. However, the climatological distributions of $B$ raise the possibility that blocking at each longitude could be described by a first-order Markov process, involving just white noise and relaxation back to the local mean. In fact, the standard deviation of the $B$ variation with longitude is small enough that the amplitude of the white noise could be made independent of longitude. The implication would be that blocking is not a specific phenomenon with its own nonlinear dynamics.

However, this simple picture works only up to a point. The distribution of $B$ in the European region clearly shows an enhanced tail on the positive side. This enhanced tail biases the mean value that would be used in the statistical model and therefore makes it somewhat inconsistent. It also strongly suggests the occurrence of nonlinear processes tending to support the occurrence of blocking events with such positive $B$ signatures. In contrast, in the eastern Pacific blocking region it is the enhancement of the negative tail, corresponding to strong zonal flows, that is marked. Hence, in this region the nonlinear processes associated with the occurrence of strong zonal flow events are more strongly highlighted. The skewness profile supports this perspective, being positive only in the European–Asian region. However, further diagnosis might suggest the enhancement of positive as well as negative tails in the distributions of $B$ in other regions.

The results that the proportion of SB events that last at least 5 days (and are then classified as SBEs) is much larger in Europe and that the rate of population decline with duration is lower there than elsewhere are not necessarily inconsistent with the first-order Markov model. This is because the largest mean value of $B$ that would be relaxed toward occurs in the European region. However, the logarithm of the population curve against duration would be a straight line, whereas the curvature of the actual curve is important in giving the number of long-lasting SBEs. In addition, the results that the largest SBE intensities are found in the eastern Pacific and that the intensity of SB is generally largest in the autumn are not consistent with the simple statistical model, which would suggest that they should occur in the European region.

The use of a single central blocking latitude (CBL) for every longitude allows for the consideration of blocking as a function of one spatial dimension, longitude, and time. The decision to follow PH and use a CBL that does not change in time (though a small latitudinal band is allowed) is a pragmatic one. If it were relaxed and the latitude was allowed to vary in time, then a choice would also have to be made over whether to follow the storm-track latitudinal displacement in any particular period and how the time-scale of this period for averaging should be defined. The analysis of blocking as a function of longitude is very convenient for analysis and presentation and is consistent with the notion of blocking the eastward progression of storms. However, it has recently been found by Berrisford et al. (2007) that for the Southern Hemisphere, with its double winter jet, it is preferable to extend the analysis to a consideration of $B$ as a function of two spatial dimensions. Woolings et al. (2008) have recently used...
this 2D index for an analysis of wave breaking in the Northern Hemisphere winter. The European sector still stands out, but the focus of Woollings et al. (2008) is on the many wave-breaking events that are also found poleward of the oceanic jets and storm tracks, and their relationship to the North Atlantic Oscillation (NAO) and Pacific variability. Because of their location with respect to the storm track, these events are not blocking in the classic sense.

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