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Climatological features of blocking anticyclones in the Northern Hemisphere

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ABSTRACT

Blocking anticyclones have long been of interest to the atmospheric science community because of their profound effect on local and regional climates. Previous climatologies of blocking anticyclones have been performed using subjective or objective techniques to locate individual blocking events using observational data sets typically of greater than 10 years. In this study, a 3-year climatology of Northern Hemisphere blocking anticyclones was developed using ECMWF analyses to derive a comprehensive set of blocking anticyclone characteristics, including location, frequency, duration, intensity, size, seasonal and regional distribution, and relationship to precursor cyclones and jet streaks. Results show that preferred blocking regions were located over the eastern Atlantic Ocean, the Pacific Ocean, and the Ukraine/western Russia and that most blocks occurred in winter, as seen in other climatological studies. Block half-wavelengths, which averaged about 3000 km, were positively correlated with block intensity at the 99% confidence level. However, block duration, which averaged 8.6 days, was only weakly correlated with both size and intensity. Also, this study reveals that all 63 blocking anticyclones were preceded by an identifiable surface cyclone, which began its most rapid deepening 36 h or more prior to block onset. However, only 34 of these cyclones could be characterized as "explosively" developing, with half of these preceding winter season blocks and none preceding summer season blocks. A positive correlation was found between the intensity of blocking anticyclones and the intensity of the precursor cyclone development, significant at the 95% confidence level. This correlation was also found for events occurring over the oceanic regions. Finally, the intensity of the precursor cyclone development was correlated with other blocking characteristics and no significant relationships were found.

1. Introduction

Blocking anticyclones are large-scale, mid-latitude atmospheric phenomena that have captured the interest of the meteorological community for several decades. It has long been recognized that blocking anticyclones have a profound effect on local and regional climates in the immediate blocking domain (Rex, 1950; Illari, 1984) as well as in regions upstream and/or downstream of the blocking event (Quiroz, 1984; White and Clark, 1975). In the past, several climatological investigations have been performed using large observational data sets (i.e., 10 years or more) in order to determine the predominant characteristics of blocking anticyclones, including favored development regions, duration, preferred seasonal occurrence, and frequency of occurrence (Rex, 1950; Triedl et al., 1981; Lejenäs and Økland, 1983). However, most of these studies tend to focus on limited regions (White and Clark, 1975), a particular season (Dole and Gordon, 1983), a few characteristics of blocking events (Rex, 1950), or their relationship to other events such as mid-latitude cyclones (Alberta et al., 1991). Taken together, these and many other studies have shown that in the Northern Hemisphere, blocking

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anticyclones occur largely in the eastern Atlantic and Pacific regions downstream from both the North American and Asian continents, respectively, and the associated primary storm tracks that are found east of these continents. Blocking anticyclones have also been shown to occur most frequently in the cold season (October to April), and individual events can persist for three weeks or longer. Some studies have revealed the presence of a third region of block formation in western Russia (Triedl et al., 1981; Dole and Gordon, 1983) downstream from another storm track that stretches across the northern Mediterranean region and Turkey and continues into the Caspian Sea (Whittaker and Horn, 1982).

In last decade, there has been considerable attention paid to the relationship between blocking anticyclones and other mid-latitude features. The two features that have been related to blocking events most frequently are mid-latitude cyclones that precede blocking events (Shutts, 1983; Colucci, 1985, 1987; Mullen, 1987; Tsou and Smith, 1990; Alberta et al., 1991) and low-frequency planetary waves (Blackmon et al., 1977; Hansen, 1986; Lejenäs and Madden, 1992). While migrating cyclones and blocking anticyclones are of different spatial and temporal scales and, in general, would seem to possess different characteristics, they are dynamically linked (Dole, 1983; Frederiksen, 1982, 1983; Colucci, 1985). Shutts (1983) used a barotropic model to demonstrate the importance of an ensemble of cyclone-scale eddies in the maintenance of blocking anticyclones. Colucci (1985) and Shutts (1986) have demonstrated the importance of this mechanism in observational case studies as well. Tsou and Smith (1990) demonstrated a connection between intense cyclogenesis and block formation by presenting a conceptual model linking the two phenomena. Of course, it is also true that while a dynamical link may exist between intense cyclogenesis and block formation, not every intense cyclone results in the formation of a blocking anticyclone (Konrad and Colucci, 1988).

This study examines the observed characteristics of mid-latitude blocking anticyclones, and the upstream surface cyclones that precede block onset, in the Northern Hemisphere over a three-year period from July 1985 to June 1988. In many ways, this study is repetitive of previous climatological studies and indeed some of the results will be shown to be similar to previous studies. However, the present study is also unique in three ways. First, it provides a comprehensive analysis of a broader range of blocking characteristics over all seasons than has been previously published. Included in these characteristics are preferred formation regions and seasons, as well as duration, longitudinal expanse (size), and intensity as a function of region and season. Second, an investigation of upstream cyclones that precede block formation is conducted in a manner similar to that of Konrad and Colucci (1988), except that the present study is extended to include all seasons and the entire Northern Hemisphere. Finally, following the suggestion of Tsou and Smith (1990), a study of the occurrence of a jet stream between the upstream cyclone and block is included. The principal objective is to establish a statistical link between the occurrence and intensity of the upstream cyclones and the development and characteristics of blocking anticyclones.

2. Data and methodology

In this study, 3 years of ECMWF gridded data analyses covering the period from July 1985 to June 1988, from the WGRP/TOGA Archive II provided by the National Center for Atmospheric Research (NCAR), were used. The ECMWF analyses are global 2.5° latitude by 2.5° longitude uninitialized gridded fields composed of both surface and free atmosphere variables twice daily. The free atmosphere variables were provided for mandatory levels from 1000 to 10 mb. A thorough description of these analyses is given in Trenberth (1992). The variables used in this study were 500 mb geopotential height, 300 mb u and v wind components, and sea-level pressure.

Although long enough to provide a reasonable sample of blocking events, the three-year study period is short compared to other climatological studies. A relatively short period was chosen in order to make it practical to visually confirm blocks identified using the objective classification technique described below, to manually calculate the blocking and upstream cyclone characteristics of each case, and to observe the relevant jet stream characteristics for each case. Thus, we are confident that we have identified all blocking anticyclone events that occurred during the three-year period and that we have properly assigned any relevant upstream cyclone/jet stream occurrences.

The formulation of an appropriate blocking definition is itself an intriguing problem. In fact, no common definition of blocking exists, and almost all definitions contain some subjectivity. Rex (1950) defined blocking as follows;

(i) the basic mid-latitude (westerly) flow must be split into two branches;

(ii) each branch (jet) must transport appreciable mass;

(iii) the double jet system must extend over at least 45° longitude;

(iv) a sharp change from more zonal flow to meridional flow must occur across the region of the split;

(v) the pattern must exist with recognizable continuity for at least 10 days.

White and Clark (1975) added to the Rex definition by requiring that the anticyclone be north of 35°N and have an amplitude of 5° latitude or greater. Triedl et al. (1981) defined a blocking event as the simultaneous existence of a high pressure region with closed isobars on surface pressure charts and closed height contours on 500 mb charts such that the mid-latitude flow is split into two branches. They also specified that the anticyclone should exist north of 30°N latitude and persist for five days or more. They found that typical mid-latitude blocking anticyclone events are dipoles consisting of a positive height anomaly (high) around 60°N and a negative height anomaly (low) around 40°N. Lejenäs and Økland (1983) developed an index based on this latter result of Triedl et al. (1981) and the zonal index of Namias and Clapp (1951). The Lejenäs–Økland (LO) index is defined as:

$$LO = Z40° - Z60°, \tag{1}$$

where Z represents the 500 mb geopotential height in meters at the respective latitudes. The index can be conveniently displayed on a Hovmöller diagram (Hovmöller, 1949), with longitude on the x-axis and time on the y-axis. Regions on the Hovmöller diagram where the LO index is less than zero specify regions where a blocking event could exist (see example in Fig. 1). In order to include only those events on a spatial scale similar

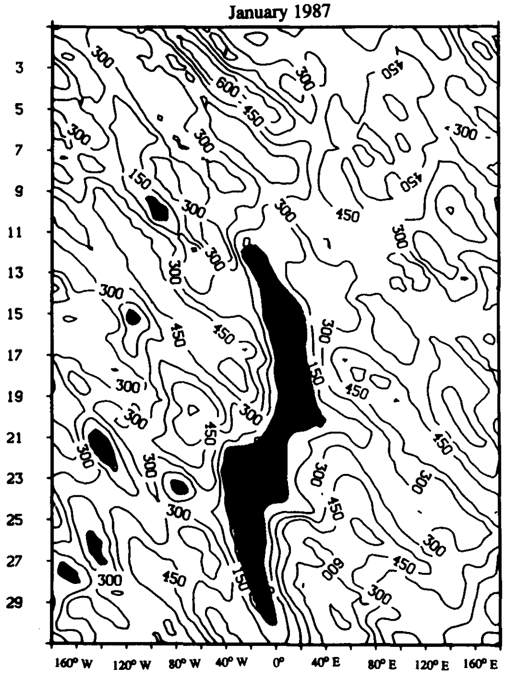

Fig. 1. Hovmöller diagram displaying the Lejenäs–Økland Index for January 1987. See text for definition. The abscissa is longitude (degrees) and the ordinate is time (days). The contour interval for the LO index values is 150 gpm. The shaded regions are values less than zero.

to the definition of Rex (1950), Lejenäs and Økland (1983) included the additional condition that

$$LO(\lambda) = (LO(\lambda - 10°) + LO(\lambda) + LO(\lambda + 10°))/3 < 0, \tag{2}$$

where λ is the longitude. This condition can be applied over all longitudes on a given day and in their investigation meant that an LO index that was negative over a span of 30° longitude indicated a blocking event. Also, it should be noted here that blocking events which satisfy this condition tend to be long-lived (Lejenäs and Økland, 1983). In this way Lejenäs and Økland attempted to remove subjectivity from their definition of a blocking event. However, in recognition of the fact that the blocking dipole will not always be located at 40° and 60°N, Madden and Lejenäs (1989) modified the LO index in their study of eastern Atlantic and European blocking events to be the difference between the 500 mb geopotential heights at 45° and 65° N. Throughout the course of this work, it was found that even if the location of the blocking dipole was significantly different (10° to 20° latitude) from 40° and 60° N a distinct signature (numbers that are less negative than those in Fig. 1 or *even slightly positive*, but less than about 50 gpm) was still imparted on the Hovmöller diagram.

The blocking anticyclone definition used in this study was formulated by combining features contained in the definitions identified above. The resulting set of criteria were useful not only in identifying blocking events, but also in separating blocking events in the same region that occurred temporally close to one another, in recognition of the fact that blocking events can be clustered in time and space (Illari, 1984). Additionally, this definition facilitated the proper identification of the preceding surface cyclone, its central pressure, deepening rate, and jet stream features. This working definition is as follows.

(a) The Rex criteria must be satisfied for an anticyclonic flow region at 500 mb with the exception that the minimum duration (criterion (v)) must be 5 days (Triedl et al., 1981) and this region must extend (criterion (iii)) over 30° longitude (Lejenäs and Økland, 1983).

(b) A negative or small positive LO index must be present on the Hovmöller diagram(s).

(c) Criteria (a) and (b) must be satisfied together from 24 h after onset to 24 h before termination.

(d) The anticyclone should be north of 35° N and have an amplitude of 5° latitude or greater (White and Clark, 1975) (the amplitude is measured as the distance between the farthest northward extent of the "RC" contour and a line connecting the upstream and downstream inflection points on the wave in which the blocking event is embedded (see Fig. 2)).

(e) Onset is defined to occur whenever an anticyclone occurs that satisfies criteria (d) and either (a) or (b).

(f) Termination is defined to occur whenever the block fails to satisfy criteria (d) and either (a) or (b) for 24 h.

This definition establishes a consistent set of guidelines for uniformly determining block onset and termination, from which blocking anticyclone lifetimes were determined, and location at both 0000 and 1200 UTC. Note that several components of the Rex definition require subjective evaluation of the 500 mb height fields. Furthermore, a precise upper limit of the LO index value applicable to all blocking events can not be established. Therefore, the blocking definition used here is not completely objective but must be accompanied by a visual subjective evaluation of the 500 mb height fields.

In addition to block lifetime and location, two other characteristics, block intensity and size, were determined once daily at 0000 UTC and then averaged over the lifetime of the event. To determine the intensity of each event, we introduce here a quantity known as the blocking intensity (BI), defined as

$$BI = 100.0 \cdot ((MZ/RC) - 1.0), \tag{3}$$

where RC is the 500 mb geopotential height contour value (gpm) representative of the wave in which the blocking event is embedded. To minimize subjectivity, RC was determined by meeting the following conditions (see Fig. 2 for an example):

(a) RC must represent the full wave length, between the trough lines of the upstream and downstream trough;

(b) RC may not be a closed contour;

(c) RC is the middle contour of the open contours along the wavelength (if it appears that more than one contour is a candidate for this choice, the contour with the higher value is chosen).

MZ represents the maximum 500 mb geopotential height (gpm) in the closed anticyclone region or on the ridge line associated with the block. Therefore, BI is a measure of the average maximum height of the block over its lifetime normalized to adjust for daily and regional anomalies. Subtraction of 1.0 and multiplication by 100 yields a quantity that typically ranges in magnitude from 1.0 to 10.0. Following the subjective assessment of intensity by Rex (1950), each event is characterized as strong ($BI > 4.55$), moderate ($4.55 > BI > 2.55$), or weak ($BI < 2.55$). The rationale for this choice of intensity limits is discussed in Section 3. The RC height contour was also used to determine the half-wavelength (size) of the blocking ridge. The half-wavelength was determined as the distance between the upstream and downstream inflection points on the RC contour. The daily position of the blocking anticyclone was set as the latitude and longitude at which MZ was located.

After a blocking case was identified, the sea-level pressure field was searched for the existence of precursor, upstream cyclones. The importance of upstream cyclones to block occurrence has been documented in a number of studies (see Introduction). However, a complete climatology of the relationship between blocking anticyclones and upstream cyclones has never been presented for all seasons and over the entire Northern Hemisphere using our methodology or methodologies similar

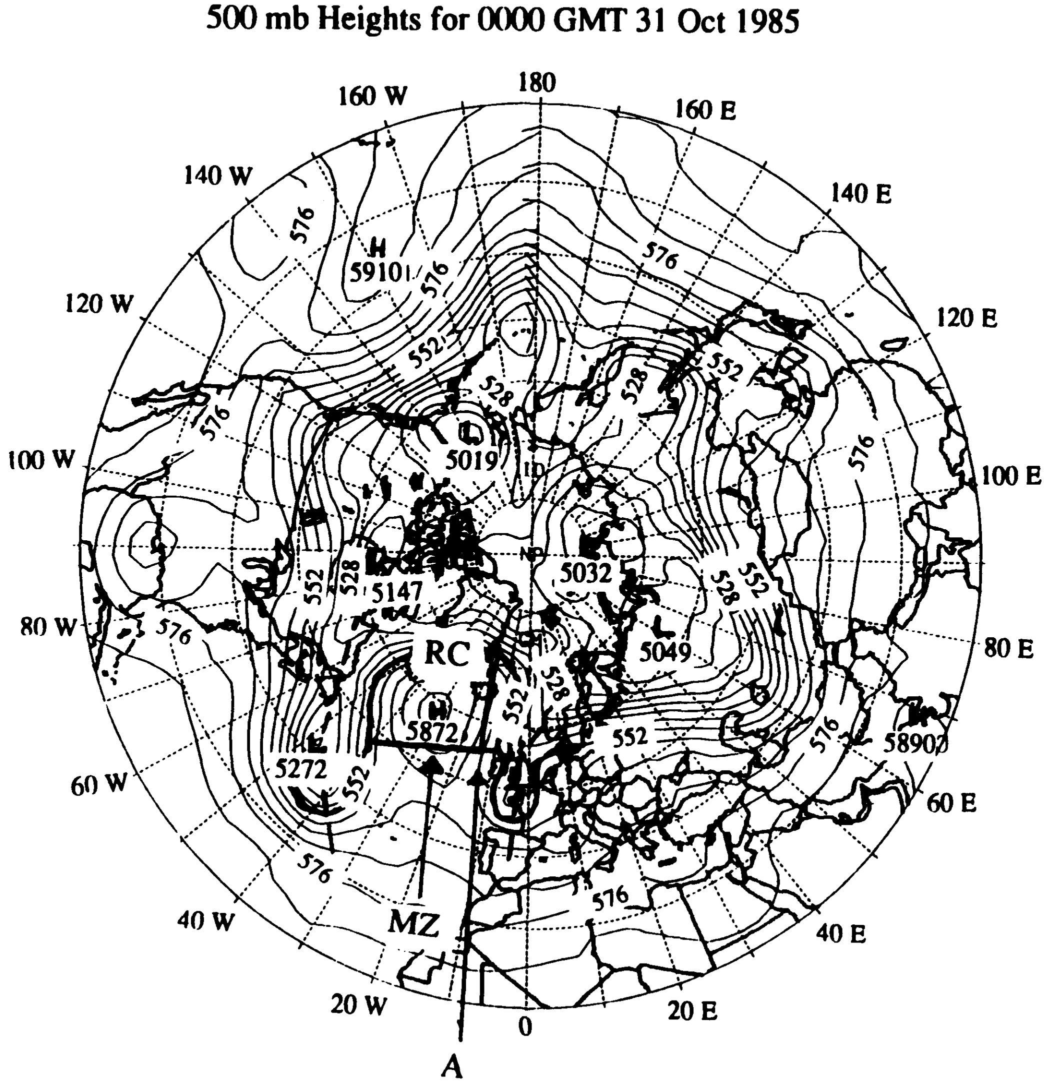

Fig. 2. An example of RC (see text), half-wave length, and maximum height (MZ, gpm) for a blocking anticyclone. The isoheights are contoured every 60 gpm, the bold contour is the RC contour and the dashed lines are trough axes. The half-wavelength is the distance represented by the line connecting the two inflection points. The amplitude is a line (A) connecting the farthest northward point on RC and the line used to measure half-wavelength.

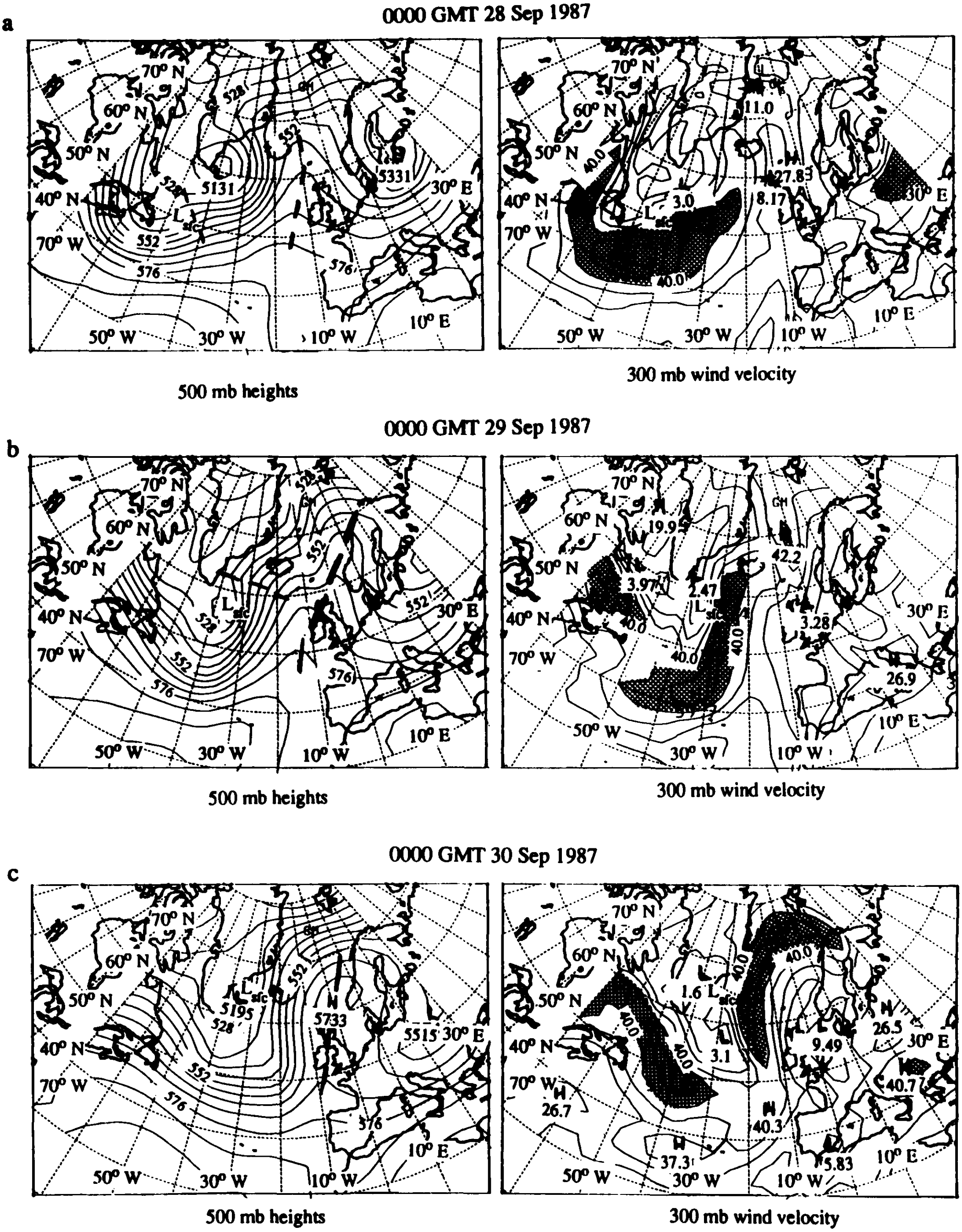

Fig. 3. An example of the Tsou and Smith model for block formation displayed in three steps where; (a) is step 1, (b) is step 2, and (c) is step 3 as summarized in text. For each part the upper panel contains 500 mb contours (gpm) with the large-scale ridge (and short-wave ridge in addition on (a) and (b)) marked with heavy dashed line and surface cyclone marked with large *L*. The lower panel contains 300 mb isotachs (ms^{-1}) with values greater than 40 ms^{-1} shaded.

to Konrad and Colucci (1988). Each case was examined to determine if a surface cyclone existed in association with a 500 mb short wave embedded within a larger-scale trough upstream from a quasi-stationary 500 mb ridge or a configuration similar to those suggested by Dole (1983) and Tsou and Smith (1990). Statistics on the lead time of the precursor cyclones in advance of each block onset, as well as the relative position and rate of cyclone development were kept. The rate of cyclone development is represented in Bergerons (Sanders and Gyakum, 1980), where one Bergeron is defined as a central pressure decrease of 12 mb $(12\text{-h})^{-1}$ multiplied by the factor ($\sin\phi/\sin 60°$N), where ϕ is the latitude of the cyclone center at the mid-point of the 12-h period. As defined in Sanders and Gyakum (1980), one Bergeron or more represents explosive cyclogenesis. Additionally, the 300 mb wind speeds were examined to study the relationship between block onset and upstream jet streak occurrence. This part of the investigation was motivated by the work of Tsou and Smith (1990), who presented a conceptual model connecting the preceding upstream cyclogenesis and the onset of a blocking anticyclone through the development of an intervening jet maximum. This conceptual model can be summarized as follows; (1) intense or explosive cyclogenesis begins, perhaps in response to an upper-level jet streak (Uccellini et al., 1987), upstream from an existing large-scale, quasi-stationary ridge some 24 h or more prior to block onset; (2) as explosive development progresses, the 500 mb short wave amplifies and an upper-level jet streak appears downstream (upstream) of the trough (ridge) following the rapid surface development; (3) as the cyclone approaches maturity and the amplified 500 mb short-wave ridge becomes in phase with the large-scale ridge, the intensified jet streak aids, primarily through enhanced upper-level anticyclonic vorticity advection, block formation.

An example of this scenario (Fig. 3) is presented here to demonstrate the Tsou and Smith (1990) conceptual model and the application of our blocking definition (Table 1). In the 72 h (starting at 0000 GMT 25 September 1987) prior to the first map time shown in Fig. 3, a migrating ridge feature in the 500 mb height field (not shown here) could be followed as it propagated from the central to the far eastern Atlantic. In the following synoptic discussion, all map times are 0000 GMT. On 25 September, this migrating ridge was located at approximately 40° W longitude in the central Atlantic to the south–southeast of Greenland. By 27 September (Table 1), this ridge feature, now located along 20° W longitude, did not meet our criteria for a blocking event.

On 28 September (Fig. 3a), the large-scale ridge feature became nearly stationary at approximately 10° W longitude and, again, did not meet our criteria for a blocking event. The associated surface cyclone was located at 47.5° W, 50° N and had a central sea-level pressure value of 995 mb (Table 1). Also, the 500 mb map shows the short-wave ridge feature that was associated with the surface low. At 300 mb, a large jet maximum was wrapped around the base of the upstream 500 mb trough and the surface cyclone was located on the cyclonic side of the jet axis. After 24 h (29 September, Fig. 3b), the surface cyclone had moved northeastward and was located southeast of Greenland with a central pressure of 978 mb. The

Table 1. *Date each criteria are fulfilled using the definition of a blocking event for this study*

(a) Criterion met (yes (Y), no (N), and not applicable (N/A))

date	9/27	9/28	9/29	9/30	10/1	10/2
criterion						
A	N	N	N	Y	Y	Y
B	N	N	N	N	Y	Y
C	N/A	N/A	N/A	Y	Y	Y
D	Y	Y	Y	Y	Y	Y
E	N/A	N/A	N/A	Y	N/A	N/A
F	N/A	N/A	N/A	N/A	N/A	N/A
G	N	N	N	Y	Y	Y

(b) Block intensity calculations.

MZ. (m)	N/A	N/A	N/A	5733	5771	5794
RC (m)	N/A	N/A	N/A	5520	5580	5640
BI	N/A	N/A	N/A	3.85	3.42	2.73

(c) Precursor cyclone central sea-level pressures (mb).

central sea-level pressure	N/A	995 mb	978 mb	983 mb	N/A	N/A

Letters A through F correspond to the appropriate criterion in Section 2. G denotes whether this event qualifies as a block. All dates are 0000 GMT.

Table 2. *Regional domains and seasons used in this investigation*

Season	Months
summer	July–September
autumn	October–December
winter	January–March
spring	April–June
Regional domain	**Longitudinal boundaries**
Atlantic Ocean region	80° W to 40° E
Pacific Ocean region	140° E to 100° W
continental region	40° E to 140° E, 100° W to 80° W

large-scale 500 mb ridge was located from 70° N, 20° E southwestward toward 45° N, 15° W and still did not meet our criteria for a blocking anticyclone event (Table 1). The short-wave 500 mb ridge associated with the surface cyclone amplified and was moving up the western side of the large-scale ridge. The jet maximum at 300 mb had propagated up the eastern side of the 500 mb trough. By 30 September (Fig. 3c), 48 h after rapid cyclogenesis began and 24 h after the 300 mb jet moved into a favorable position, the short and long-wave ridges had merged and the large-scale ridge finally met the criteria for a blocking event as defined in this study. The surface cyclone continued to move north–northeastward up the western side of the block and was decaying (Table 1).

Finally, the results were examined in more detail by stratifying the results by season and by region. A complete blocking year is defined as starting on 1 July and ending on 30 June, consistent with Rex (1950) and Quiroz (1987). Table 2 defines the seasons of the blocking year. This definition of blocking "seasons" conforms to the natural variability of blocking anticyclone events, as will be seen in the next section. The data were examined by partitioning the results into three domains, the Atlantic, Pacific, and Continental (see Table 2 for longitudinal limits). The motivation for separating the results into these regions derives from analyses shown in Whittaker and Horn (1982) and Hansen (1986). The analyses of Whittaker and Horn (1982) show major storm tracks, the Atlantic and Pacific tracks, lying east of North America and Asia, respectively, and another that stretches over the northern Mediterranean east to the Caspian Sea region. Fig. 5 in Hansen (1986) shows, using the mean 500 mb height anomalies synthesized from zonal wave numbers 1–4 for 1980 to 1984, positive anomalies located downstream from the storm tracks of Whittaker and Horn (1982). Therefore, these analyses suggest that a climatological signature exists in the storm track/500 mb height anomaly configuration for the observed Atlantic and Pacific block formation regions, and also suggests that a third preferred block formation region exists over the west Asian continent. This continental block formation region has been found in other studies (Triedl et al., 1981; Dole and

Table 3. *Regional domains and seasonal distribution of (a) number of blocking events/average duration in days of each blocking event, and (b) total number of blocking days/days at least one blocking event present*

(a) Number of events/average duration

Region	summer	fall	winter	spring	total
all events	10/7.5	16/8.4	21/9.6	16/8.2	63/8.6
Atlantic	2/7.0	8/7.4	9/11.0	10/8.8	29/9.0
Pacific	5/7.2	4/7.9	8/8.6	2/6.3	19/7.9
continental	3/8.2	4/14.3	4/8.4	4/7.4	15/8.7

(b) Total days/days at least 1 event present

Region	summer	fall	winter	spring	total
all events	74.5/60.5	134/116	201.5/158	130.5/125	540.5/460
Atlantic	14	59.5	98.5	87.5	259.5
Pacific	36	31.5	69.5	13.5	150.5
continental	24.5	43	33.5	29.5	130.5

Gordon, 1983) and was also verified by our investigation. By separating the results into 3 regions, it can be determined if there are any significant statistical differences between the characteristics of blocking events over oceanic and continental domains.

3. Seasonal and regional characteristics of blocking anticyclone events

In this section, we will examine the regional and seasonal distribution of blocking characteristics. As discussed in Section 2, there is sufficient evidence to suggest that expressing the climatology in terms of 3 regions, with 2 oceanic and 1 continental domain, may prove to be informative. The motivation for examining the results in this manner was to determine if there were any significant differences between the characteristics of blocking anticyclones that form over continental and oceanic regions and their preceding cyclones. Table 3a and Fig. 4a show the basic frequency and lifetime statistics for all events. Over the three-year period there were 63 observed cases, an average of 21 annually (Table 3a). This is consistent with the average annual occurrence of blocking events found in the results of Lejenäs and Økland (1983) and Triedl et al. (1981). Stratifying the results by region demonstrates that blocking events were more numerous in the Atlantic region (29 events), followed by the Pacific region (19 events), and then the continental region (15 events). Thus, blocking events over land were almost as common as those that appear over the Pacific Ocean. The ratio of Atlantic to Pacific events (1.52) was smaller than that found in the investigations of Triedl et al. (1981) and Lejenäs and Økland (1983), whose results were stratified into only Atlantic and Pacific hemispheres. The monthly statistics for all events (Fig. 4a) shows that January, February, and March (winter season) and October, November, and December (fall season) encompass two distinct blocking maxima; while April, May, and June (spring season) and July, August, and September, (summer season) are representative of two blocking minima. Further examination of Table 3a and Fig. 4a reveals that blocking occurred most frequently in the winter season and least frequently in the summer. Over the Atlantic region, the frequency was roughly equal throughout three seasons (November–June) with a pronounced summer minimum (July–September). Over the Pacific region, there were two frequency maxima with the primary maximum in the late fall and winter (November–March) and a secondary summer maximum (July–August). There were also two frequency minima over this region, the first in late summer/early fall (September and October) and the second throughout the spring (April–June). The most striking feature of these results is that the continental region displayed little seasonal variation in blocking occurrences. Finally, seasonal occurrences of blocking events over the Atlantic and Pacific regions were qualitatively similar to the results in Fig. 6 of Lejenäs and Økland (1983).

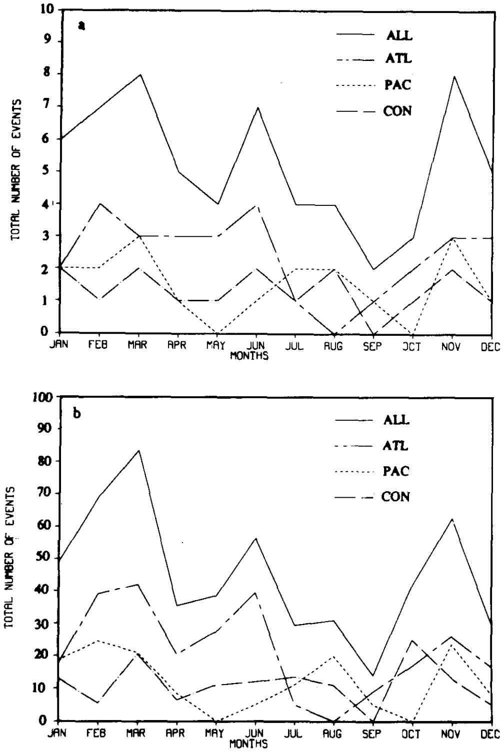

Fig. 4. A monthly summary of blocking anticyclone occurrence for: (a) the total three-year frequency of occurrence; (b) total days for all blocking events and for Atlantic, Pacific, and continental region events.

An examination of the total number of days/days on which there was at least one blocking event in Table 3b reveals that there were 540.5/

460.5 blocking days associated with the entire sample. The *total number of days* is the sum of the number of days assigned to each blocking event, while the *days on which there was at least one blocking event* is the number of days on which one or more blocking event(s) were occurring over the entire Northern Hemisphere. The difference between these two numbers is the number of simultaneous blocking days (more than one event present). Blocking events occurred in the Northern Hemisphere 42.4% of the time over the three-year period and there were 80 (7.3% of all) days in which there were simultaneous blocking events. As expected, the largest and smallest total number of days (201.5 and 74.5) were in the winter and summer, respectively. The winter months also had the greatest number of simultaneous blocking days (43 days or 15.9% of winter days), and there was at least one event present 58.5% of the time. The least number of simultaneous blocking days was in the spring (5 days or 1.8% of spring days), and the season in which a given day was least likely to have at least one blocking event present was summer (21.9%). Examining the total days results by region, blocking occurred on 23.7%, 13.7%, and 11.9% of all days over the Atlantic, Pacific, and Continental regions, respectively. The seasonal distribution of total number of days in each region was roughly parallel to the seasonal distribution of total blocking occurrences with one notable exception, the Continental region had a fall peak in the total number of days.

The average duration (Table 3a) of a blocking event in the three-year period was 8.6 days. Atlantic and Continental blocking events were, on average, more persistent than Pacific blocking events (approximately 9 days versus 8 days). Additionally, Fig. 5a demonstrates that most events lasted 5 to 7 days with a rapid decrease in the number of events persisting longer than 10 days. A regional breakdown (Fig. 5b) shows that of the 17 blocking events lasting 10 days or longer, 13 of them were Atlantic or Continental blocking events, including the three most persistent events. A seasonal breakdown of the average durations (Table 3a) reveals that winter (summer) blocking events were the most (least) persistent, lasting 9.6 days (7.5 days). As expected, Atlantic and Pacific region blocking events were most persistent in the winter, lasting 11.0 and 8.6 days, respectively. However, Atlantic region events were least persistent in the summer (7.0 days), while Pacific region blocking events were least persistent in the spring (6.3 days). This result along with total occurrences and days demonstrates the rarity of blocking events in the Atlantic region summer and Pacific region spring. In the continental region, the average durations were relatively similar in all seasons except fall, when significantly greater persistence is evident. However, this statistic and the total number of days for Continental fall events is dominated by one event which persisted for 25 days.

Fig. 6 shows the longitudes of preferred block formation for all 63 cases and for each season separately. Fig. 6a, the annual summary of all events, shows a broad block formation region over the Pacific ocean from 160° E to 130° W, a well-defined maximum over the eastern Atlantic ocean around 10° W, and a secondary maximum at 40° E over the Ukraine and western Russia. These results are consistent with those of the studies mentioned previously, but in particular with those of Triedl et al. (1981). In general, these preferred formation regions are on the eastern end of three major storm track regions (Whittaker and Horn, 1982), and just west of the positive 500 mb height anomaly centers for wave numbers 1–4 (see Hansen, 1986). Breaking the position results down by season shows that the broad Pacific formation region shows little seasonal drift except for spring, when there is a noticeable absence of blocking events. In the Atlantic, there is a noticeable absence of summer blocking events. However, as the frequency increases in the fall, the peak formation region is near 0 to 10° W. It then shifts to 20° W in winter and flattens to a broader spring peak, a result that corresponds well with the results of Rex (1950). Block occurrences over the Continental region near 40° E show little seasonal drift.

Block intensity statistics are summarized in Table 4a and Fig. 7. The average intensity (BI) and standard deviation of BI for all 63 cases was 3.55 and 1.0, respectively. The BI values in this sample exhibit a near-normal distribution with respect to the mean, a conclusion that was confirmed at the 99% confidence level by fitting a normal distribution to the BI data and performing a χ^2 goodness-of-fit test. Therefore, all blocking events that fell within one standard deviation of the mean were classified as moderate (46 events), those falling below 2.55 as weak (8 events), and

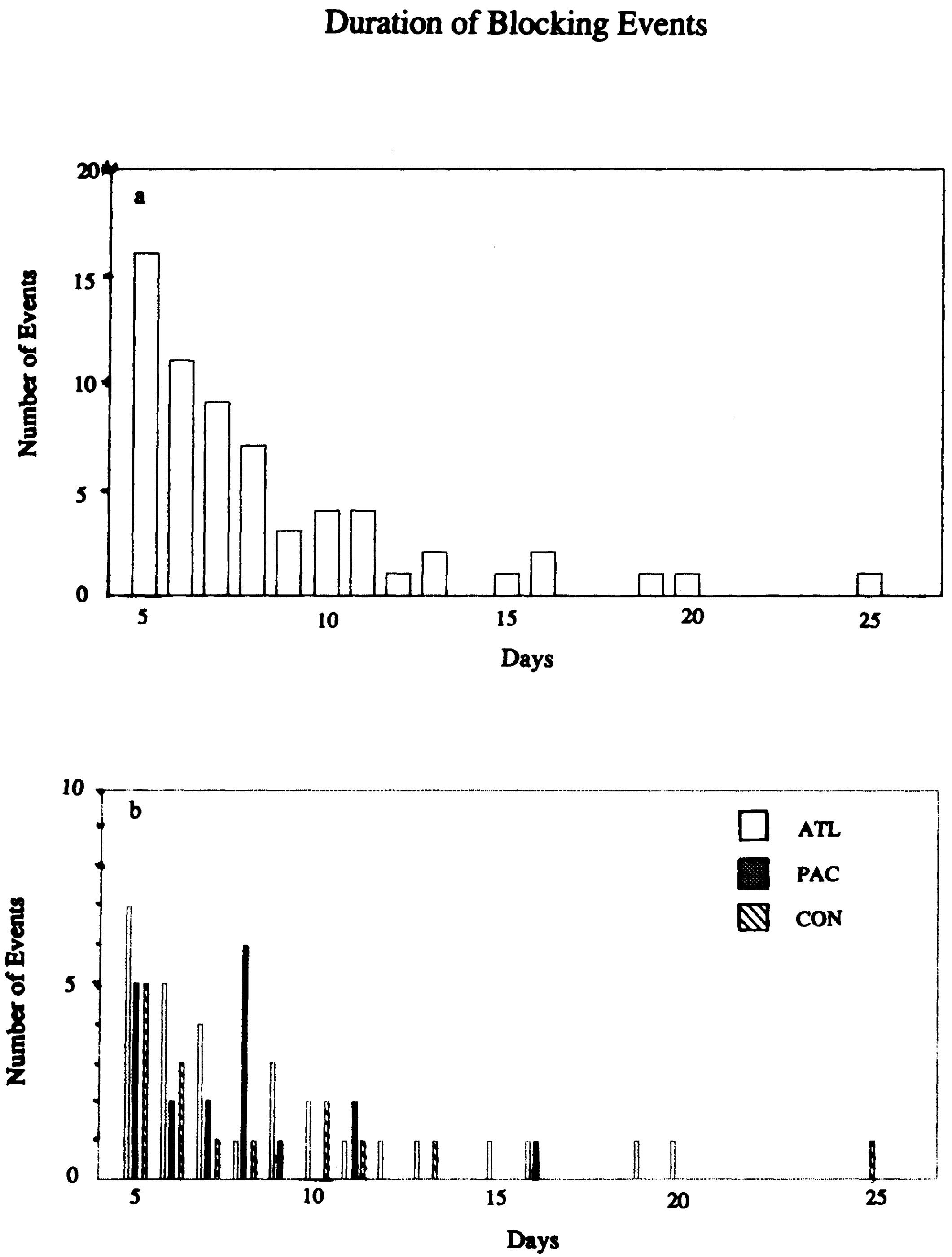

Fig. 5. Duration of individual events for (a) all blocking events, and (b) Atlantic, Pacific, and continental region events.

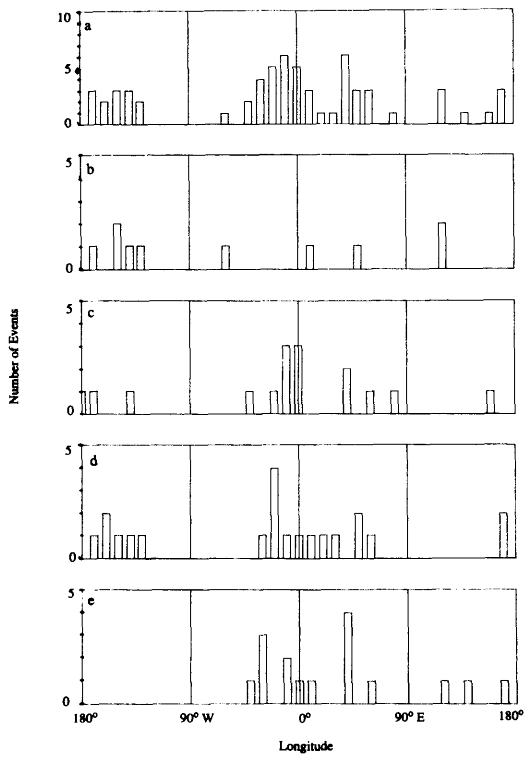

Fig. 6. Longitude of onset of blocking anticyclone events for (a) all events, (b) summer events, (c) fall events, (d) winter events, and (e) spring events.

Table 4. *Average block intensity (BI) and half-wavelength (km) by season and region*

(a) Average block intensity

Domain	summer	fall	winter	spring	total
all events	2.5	4.1	3.9	3.3	3.55
Atlantic	2.7	4.0	4.4	3.4	3.8
Pacific	2.4	4.1	3.7	2.2	3.3
continental	2.8	4.2	3.4	3.5	3.5

(b) Half-wavelength

all events	2730	3043	3087	3129	3030
Atlantic	2601	3256	3431	3149	3252
Pacific	2838	2394	2573	2336	2580
continental	2634	3270	3341	3479	3218

those above 4.55 as strong (9 events). An examination of regional (seasonal) intensities demonstrates that Atlantic (fall and winter) blocks were on the average stronger than their Pacific and Continental (spring and summer) counterparts, with much of the overall difference being accounted for by the disparity among the regional intensities in the winter. Also, regional and seasonal differences can be accounted for, or at least partly, by the distribution of the nine strong blocking events. 8 of the 9 strong events occurred in the fall and winter seasons, and 6 (2, and 1) of these 9 events occurred over the Atlantic (Pacific, and Continental) region(s). The 9th strong event occurred in the spring in the Atlantic region. This, combined with the scarcity of Pacific blocking events in spring accounts for the particularly large difference between the Atlantic and Pacific intensities in that season. Another interesting observation is that although simultaneous blocking events were not common, 4 of the 9 strong blocking events were associated with simultaneous blocking events. This corresponds to the qualitative observations of Rex (1950) and those of Quiroz (1987), who comments in his study that some of the most spectacular blocking events occurred in association with simultaneous events.

An examination of the half-wavelength of the blocking events (Table 4b) demonstrates that, in general, Atlantic and Continental blocking events were larger than their Pacific counterparts in all but the summer season. Also, Atlantic blocks were largest in winter, Pacific blocks were largest in summer, and Continental blocks were largest in the spring. Continental blocking events were of similar size and varied seasonally much like Atlantic region blocks. In these 2 regions, the seasonal variation in size follows the seasonal variation in the latitudinal positioning of storm tracks. Examining the climatological storm tracks from Whittaker and Horn (1982), the cyclones from our 3-year data set, and the latitudinal positions (not shown) of the blocking anticyclones implies that blocking anticyclones in these two regions tended to follow the northward (southward) migration of their preceding cyclones in the summer (winter) months. This seasonal variation in latitudes may explain much of the seasonal size variation in the Atlantic and Continental regions. However, in the Pacific region, where the seasonal variation in the storm track location is much less evident, there

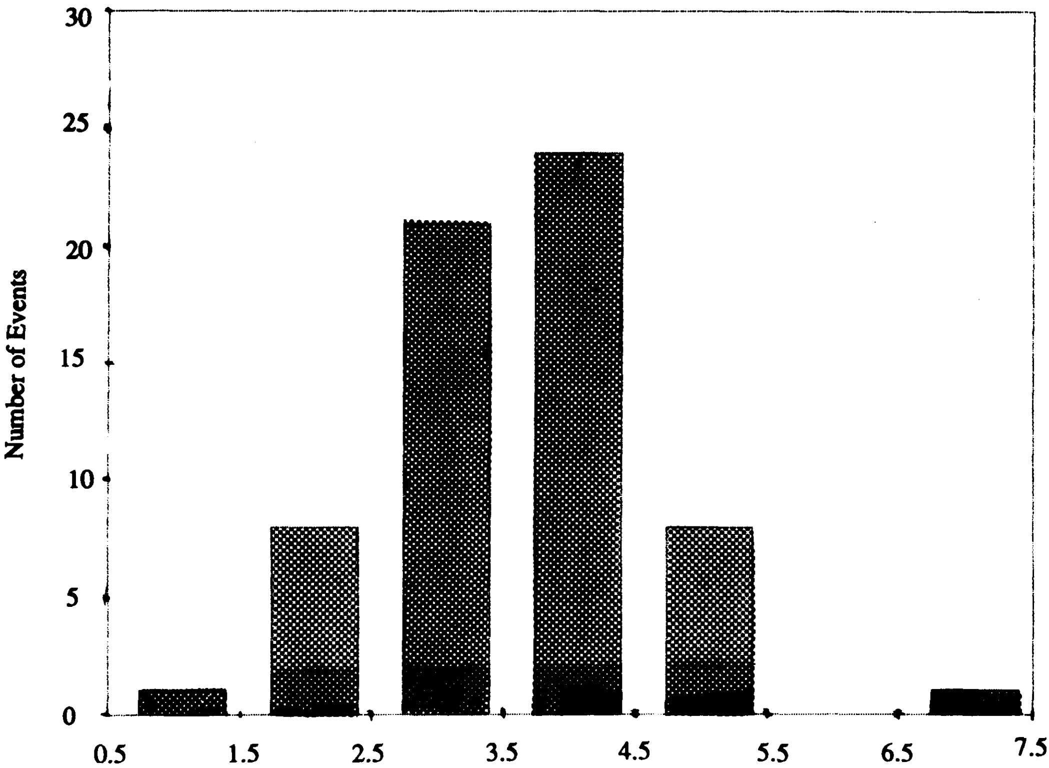

Fig. 7. Distribution of block intensities with respect to the mean. See text for definition of block intensity.

was less seasonal variation in size and latitude of blocking anticyclones, and the seasonal variation was very irregular.

Finally, a comparison of block size with the block intensity results indicates a relationship between these two characteristics, i.e., more intense blocks were also larger. Fig. 8a, which shows a scatter plot of half-wavelength versus intensity for all events, suggests a linear relationship between these two variables with a correlation coefficient of 0.47. A Z-score test assuming the null hypothesis, or no relationship exists (Neter et al., 1988), showed this result to be significant at the 99% confidence level. It should be noted here that subsequent correlations appearing in this text were also tested for significance using the Z-score test and assuming the null hypothesis. Partitioning the results into regions (Figs. 8b–d) demonstrates that this positive correlation between size and intensity is present for both the Atlantic and Continental regions (significant at the 95% confidence level) but is much weaker for the Pacific region. Block intensity and size were also correlated with duration (not shown). While positive correlations resulted, they were weak (0.20 for intensity versus duration and 0.24 for size versus duration) and were significant only at the 90% confidence level.

4. A comparison of blocking anticyclones with their precursor cyclones

One of the goals of this investigation was to establish a statistical link between the frequency and intensity of precursor, upstream cyclones and block formation and characteristics, thus answering a call for work in this area sounded by Konrad and Colucci (1988). As stated in the Introduction, it has been known for some time that a dynamic link exists between block formation and preceding

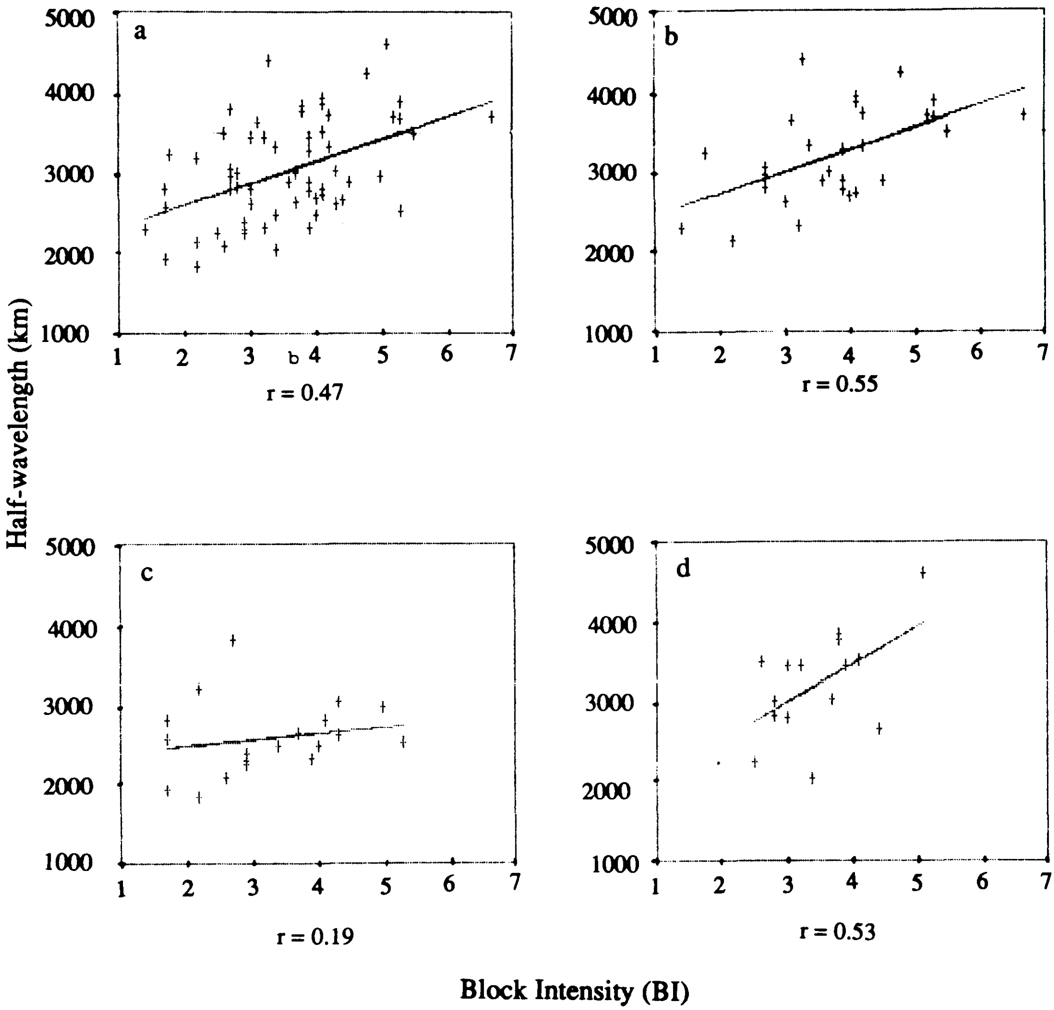

Fig. 8. Scatter plots of block intensity (abscissa) versus half-wavelength (ordinate, km) for (a) all events, (b) Atlantic region, (c) Pacific region, and (d) continental region events.

upstream cyclogenesis. The conceptual model proposed by Tsou and Smith (1990) and summarized in Section 2 provides a possible connection between the two phenomena. The applicability of this model was examined for each of the 63 blocking cases included in this study. In addition to examining 500 mb height fields, sea-level pressure maps were used to establish the presence and characteristics of precursor cyclones. Also, 300 mb winds were examined to determine if a jet maximum could be located on the downstream (upstream) side of the upper air trough (ridge), and if it formed or existed there between the commencement of surface cyclogenesis and block onset.

Table 5 provides statistics on the relative occurrence of developing cyclones associated with the 63 blocking events. First note that *all* 63 blocking events could be identified with an upstream, precursor cyclone using the criteria provided in Section 2. However, not all of the cyclones were explosively developers nor was every explosive cyclone associated with block formation. In the Northern Hemisphere, explosive cyclogenesis

Table 5. *Frequency of cyclogenesis preceding blocking events*

Total no. cyclones/total no. explosive cyclones						
Domain	summer	fall	winter	spring	total	DR
all events	10/0	16/10	21/17	16/7	63/34	0.99
Atlantic	2/0	8/7	9/8	10/6	29/21	1.05
Pacific	5/0	4/2	8/6	2/0	19/8	1.11
continental	3/0	4/1	4/3	4/1	15/5	0.71

DR represents average deepening rates in Bergerons for annual total cyclones.

occurs more frequently than block formation. Blocking climatologies, such as this one or Lejenäs and Økland (1983), show that there are typically 20 to 22 blocking anticyclone occurrences annually. Sanders and Gyakum (1980) and Roebber (1984) both found, in their one-year (calendar year) studies covering 67% of the Northern Hemisphere, more than 100 explosive cyclogenesis events. Konrad and Colucci (1988) found 141 explosive cyclogenesis events in their 7-year study covering only 50% of the Northern Hemisphere. However, they admit that this

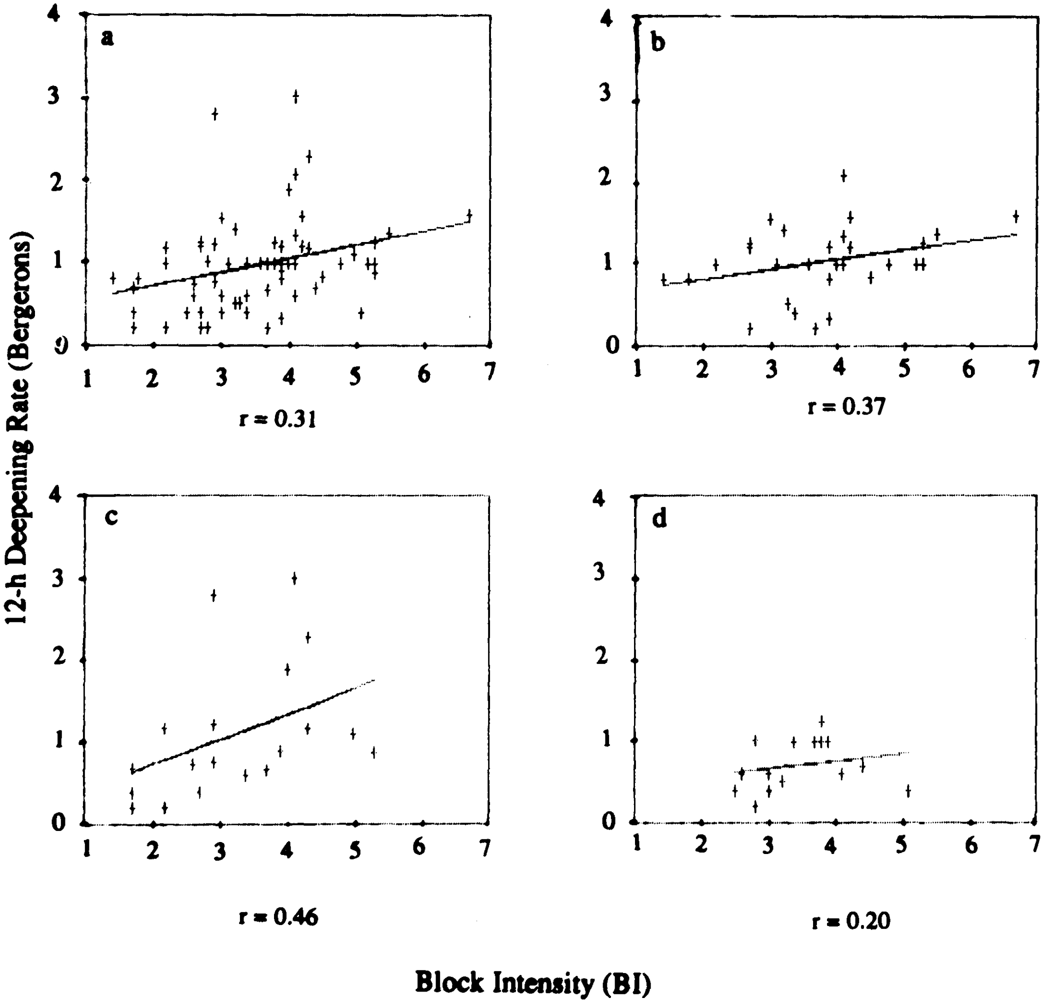

Fig. 9. As in Fig. 8 for block intensity (abscissa) versus precursor cyclone deepening rate (ordinate, Bergerons).

number is probably a low estimate due to the methods employed in locating them.

The mean deepening rates for all 63 cyclones, the 29 Atlantic cyclones, 19 Pacific cyclones, and 15 Continental cyclones were 0.99, 1.05, 1.11, and 0.71 Bergerons, respectively. In the winter, the majority of the preceding cyclones developed explosively and in the spring and fall approximately half of the total cyclones were explosive. However, in the summer none of the preceding cyclones were explosive. A comparison of the seasonal variation of the precursor cyclogenesis intensity with the block intensity discussed in Section 3 suggests that a relationship may exist between the two parameters. Fig. 9a, which displays a scatter plot of cyclone deepening rates versus block intensities for all events, shows a linear relationship between the two with a correlation coefficient of 0.31 (significant at the 95% confidence level). Therefore, in general, stronger blocking anticyclones develop when preceded by more rapidly deepening cyclones. Partitioning these results by region reveals that 72% of the Atlantic region, less than half of the Pacific region, and only one-third of the continental region blocking events were preceded by an explosive cyclone. All 3 regions exhibited similar seasonal trends. Furthermore, a regional examination of the correlation between the intensity of cyclone development and block intensity was performed. This correlation existed for the Atlantic and Pacific regions (significant at the 95% confidence level), but was weaker for the continental domain (Figs. 9b–d). Additionally, the deepening rate of the precursor cyclones was correlated with other characteristics of blocking anticyclones, such as duration and size, and no significant correlations were found.

Finally, the 12-h period of most rapid cyclogenesis typically commenced 36–72 h before block onset (48 of 63 cases), and during this period the surface cyclone could always be found 10° to 50° longitude upstream from the position of the block at onset. These results are in general agreement with those of Konrad and Colucci (1988), who examined 11, 500 mb anticyclone-cyclone vortex pairs associated with explosive cyclogenesis and found that rapid cyclogenesis began 36 h or more prior to the initiation of the vortex pair. They also found that these cyclones were located 5° to 35° longitude upstream from the vortex pairs. Regarding the correspondence to a 300 mb jet maximum, such a maximum appeared prior to the onset of blocking between the blocking ridge and the upstream 500 mb trough in each of the 63 blocking cases. In all cases, the jet maximum developed or intensified after cyclogenesis began. In 15 blocking events, it was clearly evident that these jet maxima developed on the downstream (upstream) side of the 500 mb trough (ridge) as found by Tsou and Smith (1990). In 31 of the cases, it appeared that an existing upstream jet maximum intensified and rotated around the base of the trough (as in Fig. 3). In the remaining 17 it was difficult to follow the evolution of the jet using 12-h temporal resolution data.

5. Summary and conclusions

A 3-year climatology of blocking anticyclones from July 1985 to June 1988 was derived from ECMWF analysis fields. A combination of several published criteria together with a subjective examination of the 500 mb charts on each day was used to define Northern Hemisphere blocking anticyclones. Using these cases, several characteristics of the blocking anticyclones were examined. In addition, an investigation into the presence of precursor cyclones, their characteristics, and their statistical relationships to block formation was conducted. The results were stratified by season and by region. The latter was partitioned into three regions, Atlantic, Pacific and Continental, based on analyses found in the storm track data of Whittaker and Horn (1982), the location of 500 mb positive height anomalies in Hansen (1986), and the results of earlier studies (Triedl et al., 1981; Dole and Gordon, 1983) suggesting that three preferred regions of block formation exist in the Northern Hemisphere.

Examining the results of this three-year investigation, it was found that the total annual frequencies of blocking events, total days, and duration of blocking events were similar to those of previous studies, and in particular to those of the 30-year investigations of Lejenäs and Økland (1983) and Triedl et al. (1981). In this study, the preferred regions of blocking anticyclone formation were over the Atlantic (about 10° W), the Pacific (160° E to 130° W), and over the Ukraine/western Russia (about 40° E). With the exception of the

Pacific, these preferred formation regions were similar to those found by Triedl et al. (1981). The broad formation region found in this study over the Pacific agrees with the collective results of several past studies, especially those of Lejenäs and Økland (1983). A quantitative examination of block intensity and size revealed that winter blocking events were more intense and larger than their summer counterparts, and that a correlation existed between these two characteristics significant at the 99% confidence level. Weak positive correlations were also found between intensity and size versus duration, but these results were found to be statistically significant at only the 90% confidence level.

An examination of precursor cyclones revealed that the conceptual model of Tsou and Smith (1990) reasonably described the formation of every event. In winter, cyclones that preceded blocks tended to develop at an explosive rate, while in summer no preceding cyclones developed at this rate. It was shown that a positive correlation also exists between the intensity of the preceding cyclogenesis and the resulting blocking anticyclone. However, when the preceding cyclone intensity was correlated with other blocking characteristics, such as duration and size, no significant relationships were found. Interesting differences emerged when comparing the intensity of the preceding cyclones between oceanic and continental domains. In the continental region, comparatively few preceding cyclones were explosive, and their average intensity was far less than for the two oceanic regions.

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