Is Blocking a Circulation Regime?

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ABSTRACT

The relationship between Pacific blocking and large-scale circulation regimes is investigated. The large-scale circulation regimes are obtained by cluster analysis using the k-means method and tested against significance and reproducibility. Pacific blocking is described using two different methods. In a direct approach, blocking is described by a recently developed blocking index, which is defined in terms of potential temperature anomaly on a surface of constant potential vorticity. In an indirect approach, the occurrence of extreme events is used as a proxy for blockings. Between the two methods there is a causal relationship; the direct one is an indication of the occurrence of the blocking, while the indirect one is a measure of some of the effects caused by the blocking. The results indicate that large-scale circulation regimes are related to but not necessarily tightly coupled to blocking and weather extremes in the Pacific–North America region.

1. Introduction

The influence of persistent blocking events on both baroclinic wave activity (Nakamura and Wallace 1990; Mailier et al. 2006) and on surface weather (e.g., Carrera et al. 2004) provides a good example of the strong control of the planetary waves on weather systems. This control strengthens the motivation for understanding the variability and domain patterns associated with the large-scale circulation.

One approach to identify the important planetary wave patterns is cluster analysis, in which preferred states (“circulation regimes”) are identified from estimates of the probability distribution function of the largest scales (e.g., Cheng and Wallace 1993; Kimoto and Ghil 1993a,b; Michelangeli et al. 1995; Robertson and Ghil 1999; Straus and Molteni 2004; Straus et al. 2007, hereafter S07). While assessing the statistical significance of the regimes can be demanding (Stephenson et al. 2004; Straus et al. 2007), certain common patterns have emerged from varying methodologies.

One of the common patterns, the “Alaskan ridge” (“AR”) consists of a very strong ridge in 200-hPa height anomalies over Alaska, a strong trough over eastern Canada, and weaker anomalies in the subtropics (see Figs. 1c, 2a). This regime, which has been identified using cluster analysis by a number of papers (e.g., Cheng and Wallace 1993; Robertson and Ghil 1999; Straus et al. 2007), was found by Renwick and Wallace (1996a) using linear regression analysis between the European Centre for Medium-Range Weather Forecasts day 10 rms errors over the Pacific sector and the verifying analysis height anomalies. The AR regime is associated with a Pacific blocking-like feature. Renwick and Wallace (1996a) using linear regression analysis between the European Centre for Medium-Range Weather Forecasts day 10 rms errors over the Pacific sector and the verifying analysis height anomalies. The AR regime is associated with a Pacific blocking-like feature. Renwick and Wallace (1996a) using linear regression analysis between the European Centre for Medium-Range Weather Forecasts day 10 rms errors over the Pacific sector and the verifying analysis height anomalies. The AR regime is associated with a Pacific blocking-like feature. Renwick and Wallace (1996a) using linear regression analysis between the European Centre for Medium-Range Weather Forecasts day 10 rms errors over the Pacific sector and the verifying analysis height anomalies. The AR regime is associated with a Pacific blocking-like feature. Renwick and Wallace (1996a) using linear regression analysis between the European Centre for Medium-Range Weather Forecasts day 10 rms errors over the Pacific sector and the verifying analysis height anomalies. The AR regime is associated with a Pacific blocking-like feature. Renwick and Wallace (1996a) using linear regression analysis between the European Centre for Medium-Range Weather Forecasts day 10 rms errors over the Pacific sector and the verifying analysis height anomalies. The AR regime is associated with a Pacific blocking-like feature. Renwick and Wallace (1996a) using linear regression analysis between the European Centre for Medium-Range Weather Forecasts day 10 rms errors over the Pacific sector and the verifying analysis height anomalies. The AR regime is associated with a Pacific blocking-like feature. Renwick and Wallace (1996a) using linear regression analysis between the European Centre for Medium-Range Weather Forecasts day 10 rms errors over the Pacific sector and the verifying analysis height anomalies. The AR regime is associated with a Pacific blocking-like feature. Renwick and Wallace (1996a) using linear regression analysis between the European Centre for Medium-Range Weather Forecasts day 10 rms errors over the Pacific sector and the verifying analysis height anomalies. The AR regime is associated with a Pacific blocking-like feature. Renwick and Wallace (1996a) using linear regression analysis between the European Centre for Medium-Range Weather Forecasts day 10 rms errors over the Pacific sector and the verifying analysis height anomalies. The AR regime is associated with a Pacific blocking-like feature. Renwick and Wallace (1996a) using linear regression analysis between the European Centre for Medium-Range Weather Forecasts day 10 rms errors over the Pacific sector and the verifying analysis height anomalies. The AR regime is associated with a Pacific blocking-like feature. Renwick and Wallace (1996a) using linear regression analysis between the European Centre for Medium-Range Weather Forecasts day 10 rms errors over the Pacific sector and the verifying analysis height anomalies.
Characterized by meridional flow (Rex 1950). Carrera et al. (2004) analyzed the relationship between blocking over the Alaskan region and the extreme weather events in North America and showed that blockings are accompanied by an increase in the number of extreme cold events over the region from southeast Alaska to the southern plains of the United States and an increased number of extreme warm events over western Alaska. Although the pattern of the AR regime resembles blocking, this does not mean that the occurrence of this regime guarantees that the blocking is present. The purpose of this note is to assess (i) whether the occur-

**Fig. 1.** (a)–(c) The 200-hPa geopotential height anomaly corresponding to circulation regimes obtained using $k = 3$ predefined clusters. The modified Pacific trough (MPT) regime contains 1852 days, the ArH regime contains 1400 days, and the AR regime contains 1716 days. Contour interval is 20 m with the zero contour omitted. (d)–(f) Circulation regime composites of daily potential temperature on a PV = 2 surface. Contour interval is 10 K between 290 (purple) and 370 K (red). Based on NCEP–NCAR reanalysis data.
Fig. 2. (a)–(d) The 200-hPa geopotential height anomaly corresponding to circulation regimes obtained using \( k = 4 \) predefined clusters. The AR regime contains 1044 days, the Pacific trough (PT) regime contains 1420 days, the ArH regime contains 1196 days, and the Arctic low (ArL) regime contains 1308 days. Contour interval is 20 m with the zero contour omitted. (e)–(h) Circulation regime composites of daily potential temperature on a PV = 2 surface. Contour interval is 10 K between 290 (purple) and 370 K (red). Based on NCEP–NCAR reanalysis data.
rence of the AR regime implies that blocking is present and (ii) whether all Pacific blocking events occur during this regime. Data and analysis methods are presented in section 2, results and discussion follow in section 3, and the main conclusions are summarized in section 4.

2. Data and methodology

The data used in this study consist of daily fields of horizontal winds and temperatures at all 17 pressure levels available and 200-hPa height, obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses (Kalnay et al. 1996). Daily data (0000 UTC only) for 54 winters (1949 through 2002) are used. Each winter consists of the 92-day period starting on 1 January. The original fields available on a 2.5° × 2.5° latitude–longitude grid were interpolated to a Gaussian grid corresponding to a triangular 63 truncation using an area-conserving scheme.

a. Cluster analysis

The cluster analysis used is that presented in Straus et al. (2007). We very briefly summarize the procedure here; for full details the reader is referred to S07. The daily 200-hPa height anomalies in the region 20°–80°N, 150°–330°E are low-pass filtered to retain only periods of 10 days or longer. A principal component analysis is then carried out using the filtered data for all 54 winters, with the leading 6 empirical orthogonal functions providing the basis functions for a 6D representation of the dataset and accounting for 68% of the variance. In S07, a quasi-stationary filter is applied so that periods of the most rapidly changing atmospheric states are filtered out. The cluster analysis is then applied to the set of six-dimensional principal components (PCs).

The partitioning clustering algorithm of Michelangeli et al. (1995) is applied to determine the cluster centroids (mean cluster patterns) for a number of predefined numbers of clusters k ranging from 2 to 6. Significance is assessed vis-à-vis a large number of multivariate-normal samples of synthetic data constructed using six independent Markov processes (each with the same variance and lag 1 correlation as the corresponding PC). The reproducibility of the regime centroids is assessed by comparing the cluster centroids for many randomly chosen half-length samples (within the same year). Skewness in the PCs is shown not to lead to the high significance values found in S07 (generally over 90%). A comparison of the reproducibility of the NCEP data to that of the synthetic datasets, as well as the consideration of the ratio of the variance among cluster centroids to the intracluster variance, led to the choice of k = 3 or k = 4 clusters as preferred. In this paper, as in S07, we show results for k = 3 and k = 4 clusters. Figures 1a–c, 2a–d show the regimes obtained by the cluster analysis method described above, and Table 1 contains the frequency of occurrence of each regime.

The only difference with S07 is that here we use the clusters obtained without the application of the quasi-stationary filter mentioned above. While that reduces the formal statistical significance of the cluster somewhat, the centroid patterns are virtually unchanged. In this paper, the clusters are obtained from all (low frequency) data, while filtering due to persistence is applied in the context of the diagnosis of blocking (section 2b).

b. Blocking index

To characterize the blocking events we adopt the definition of blocking index proposed by Pelly and Hoskins (2003, hereafter PH), which requires fields of potential temperature expressed on the potential vorticity surface of 2 PVU (1 PVU = 10^{-6} m^{-2} K s^{-1} kg^{-1}). According to this modern definition, the blocking index at each longitude is a measure of the difference between the average potential temperature within the latitudinal region to the north and south of that longitude. The longitude where the blocking index has a positive value is considered to experience a “local instantaneous blocking” event. To capture the observed spatial and temporal distribution of blocking phenomena (Dole 1989; Tibaldi and Molteni 1990), PH define a “large-scale blocking” event as an instantaneous blocking event that occurs for at least 15° of longitude and a “blocking episode” as a large-scale blocking that persists for at least 4 consecutive days.

Potential temperature on the PV = 2 surface was obtained by vertical linear interpolation as follows: PV is calculated at each grid point on 17 pressure levels using the method of Brunet et al. (1995). The surface on which PV takes the value of 2 PVU is found searching upward/downward on pressure levels, and where the search is unsuccessful, values at the 100-hPa level are used.

Figures 1d–f, 2e–h show maps of the composites of daily potential temperature expressed on the PV = 2

| Table 1. Frequency of occurrence of different regimes for different predefined numbers (k) of clusters. |
|-----------------|-----------------|-----------------|
|                | k = 3           | k = 4           |
|                 | AR  | ArH | MPT | AR  | ArH | ArL | PT  |
| 35%             | 28% | 37% |      | 21% | 24% | 26% | 29% |

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surface for each regime diagnosed in the cluster analysis. The composite map corresponding to the AR regime retains the larger effect of the Pacific blocking on the Pacific–North America region, but also the Arctic high (ArH) regime shows, in the same region, a meridional distribution of potential temperature favorable for blocking occurrence.

3. Results

a. Distribution of blocking events on regimes

To find the answer of the first question we want to address, the frequency of the large-scale blocking events corresponding to different circulation regimes is analyzed. Figure 3 shows the frequency of the large-scale blocking events index corresponding to different circulation regimes for the region of 150°–330°E. In the region of 150°–240°E, the highest frequency occurs during the AR regime, especially for \( k = 4 \) clusters. However, the ArH regime is also strongly associated with blocking in this region, especially for \( k = 3 \). Because the definition of large-scale blocking does not account for the temporal structure of the blocking, we attribute the presence of blocking during the other regimes to short-lived blocking events. By comparing Figs. 1b,c we notice that the maximum anomaly during the AR regime is located west of Alaska and the Alaska Peninsula is dominated by both AR and ArH regimes. In the case of \( k = 4 \) (see Figs. 2a,c for comparison), the maximum anomaly during the AR regime is located right over Alaska and the positive anomaly corresponding to the ArH has only a weak influence in that region. In Fig. 3, we also show the overall frequency of large-scale blocking events as a function of longitude (dashed line). Comparing with the frequency of cluster residence (see Table 1), the largest frequency of large-scale blocking events is smaller than any of the regime frequencies.

The number of blocking episodes (i.e., large-scale blockings persisting at least 4 days) occurring during each circulation regime is shown in Fig. 4. There is a clear distinction between the AR and the other regimes for both \( k = 3 \) and \( k = 4 \). Here the contribution from the short-lived events is filtered out. Figure 4a shows the total number of blocking episodes as function of longitude for the 54 winters (dashed line).\(^1\)

\(^1\) The total number of blocking episodes is sensitive to the duration requirement. For example, we report more blocking episodes than Fournier (2003), who uses a 6-day persistence requirement.
Although the number of blocking episodes is largest in the AR regime, there are many AR days when blocking is not present. For example, for $k = 4$, if blocking episodes would cover half of the period when the large-scale circulation is in the AR regime (assuming a persistence of only 4 days), the number of episodes would be more than 150. The maximum number of episodes obtained is 20, which indicates a relatively low occurrence of blocking episodes during the AR regime.

b. Extreme weather events and circulation regimes

To find out whether all blocking events are associated with the AR regime from another point of view, we investigate the relationship between the extreme weather events as an indicator of blocking (Carrera et al. 2004) and the AR regime. Unlike Carrera et al. (2004), the location of blocking includes all the longitudes in the North Pacific. Following Cassou et al. (2005), we define the extreme warm (cold) events as days when the daily mean 1000-hPa temperature resides in the highest (lowest) 5% of the ranked time series. Figure 5 shows the frequency of extreme warm/cold events at 1000 hPa for days when the circulation resides in the AR regime (upper panels) and ArH regime (lower panels) for $k = 4$. To test the robustness of the results in Figs. 5, 6, the 95% confidence level is estimated using a Monte Carlo algorithm, which consists of 100 realizations of surrogate data. The surrogate datasets consist of scrambled versions of the 1000-hPa daily mean temperature series for each winter.

While these percentages are greater than the 5% level expected a priori from the definition of extreme warm/cold days, they are still small. Alaska is extremely warm for up to 14% of the AR days, while central Canada is extremely cold for up to 12% of the AR days. Again, because the ArH pattern may be associated with blocking, we check if any of the extreme events occurring during the ArH regime can be associated with blocking. There is a small region over the tip of Alaska that suggests the possibility of blocking, but it is only 1% above the a priori expectation.

Figure 6 shows the fraction of extreme warm/cold events that occur within the AR (upper panels) and ArH (lower panels) regime, respectively. During the AR regime, for regions in Alaska and central Canada, this percentage is as large as 60%, but is not close to 100%. For the ArH days the percentage is even less, only 30%.

4. Summary

The number of blocking episodes that occur during the AR regime is far less than would be expected if all
AR days were associated with a blocking episode. While this number is even less for other regimes, we conclude that the majority of the AR days are not associated with blocking.

For more than half of extremely warm (cold) days in central Alaska (central Canada), the circulation resides in the AR regime. Yet for much of the region, a smaller fraction of the extremely warm/cold days is associated with the AR regime.

These results indicate that large-scale circulation regimes are not necessarily tightly coupled to local weather regimes in this region. The occurrence of the former may increase the likelihood of the latter, but there is no indication of a cause–effect relationship between them. Several possibilities are suggested. One is that the low-dimensional phase space used to diagnose the regime occurrence, in which only the largest-scale patterns are retained, is not optimal for capturing strong local anomalies. (Note the rarity of blocking events compared to the occurrence of the AR regime.) From another point of view, while both the AR regime and the AR pattern of RW are enhanced during the cold phase of ENSO (see RW and S07), their internal dynamics may be quite distinct. The geopotential height field is vertically consistent during both a blocking event and during the AR regime, yet Dole (1986) shows that during the growing phase blocking displays a baroclinic structure. Li and Conil (2003) show that the midaltitude atmospheric response to SST anomalies can be a linear baroclinic response and a nonlinear equivalent barotropic response, which is much stronger than the baroclinic response. The atmospheric internal dynamics can further favor the evolution of the baroclinic structure into an equivalent barotropic one, such as blocking. The internal dynamics of individual clusters, such as the AR pattern, remain to be understood.

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