A Dynamic Analysis of a Record Breaking Winter Season Blocking Event

Andrew D. Jensen

Department of Soil, Environmental, and Atmospheric Science, University of Missouri-Columbia, 302 Anheuser Busch Natural Resources Building, University of Missouri, Columbia, MO, 65211

Corresponding author email: jensenad@missouri.edu

Abstract

The objective of this work is to study in detail a strong North Pacific, large amplitude, long-lived blocking event that occurred during January 23-February 16, 2014. Indeed, it was 11th strongest Northern Hemisphere event lasting longer than 20 days since 1968. This event formed out of the strong ridge that was associated with the devastating drought in the Western United States during the winter season of 2013-2014. This blocking event had many outstanding dynamical characteristics, chief of which is that it survived an abrupt change in the planetary-scale flow when the Pacific North American pattern index changed from positive to negative in early February. The block then reintensified, and persisted into mid-February. Several diagnostic techniques are employed to investigate the change in the planetary-scale flow during early February 2014 that have been applied to blocking before, but aren't as well known in the blocking literature.

1 Introduction

The classical picture of blocking anticyclones consists in a long lived ($\sim 5-10$ day minimum threshold of persistence), large amplitude, geopotential height anomaly [1, 2, 3, 4]. More recently, some research groups have invoked the PV (potential vorticity) perspective in defining blocking, (see for example [5, 6]). Both methods define blocking as a significant persistent anomaly, positive height anomalies in the more classical framework, or negative PV anomalies respectively. Some blocking events are characterized by height anomalies even more extreme than usual, but are short lived, see [7]. Other blocking events are longer lived than others. However, long-lived and larger than usual amplitude don't always coincide. In this paper I investigate the dynamics of a long-lived, large amplitude event, which was associated with drought in the Western United States and also the cold temperatures in the Eastern part of the United States.

As shown in [8] blocking events are maintained by fluxes of anticyclonic vorticity into the blocking domain by synoptic-scale eddies. Moreover, several studies have examined the dynamics of blocking event life cycles by partitioning variables such as height or PV into synoptic, planetary, and interaction scales (with the interaction arising from nonlinearity in the PV tendency equation) [8, 9]. For example, in [10] North Atlantic blocking is shown to be planetary-scale dominant, while North Pacific blocking is more sensitive to transients on the synoptic-scale. As described in [8] Northern Hemisphere blocking events are maintained by nonlinear amplification between synoptic and planetary-scales. Here, the blocking event under consideration was also maintained by nonlinear amplification in the manner described in [8]. Moreover, [8, 11] explain that blocking events may not survive an abrupt transition from one planetary-scale flow regime to another. The physical mechanism is likely due to a breakdown in the planetary-scale jet stream as it transitions to a new location or regime. The event under consideration here survived just such a regime change and various techniques will be used to examine the behavior of the event during the regime change and how nonlinear interactions sustained the event. Some of these techniques will be used to present evidence for the flow regime change.

The objective of this paper is to study in detail a North Pacific, large amplitude as quantified by the block intensity index (BI), (to be explained below), long-lived blocking event that occurred during January 23-February 16, 2014, centered at 130 W. Its association with the devastating drought in California alone warrants further study of the event. However, as will be shown it had many outstanding dynamical characteristics as well, chief of which is that it survived an abrupt change in the planetary-scale flow when the PNA pattern index changed from positive to negative in early February. The event then reintensified, thus increasing its longevity. This event is also part of the drought associated ridge over the West Coast of the United States during the 2013-2014 winter that has been shown to have an anthropogenic footprint, see [12]. In this paper several diagnostic techniques will be employed and another objective of this work is to illustrate techniques that have recently been applied to blocking, but aren't as well known in the literature on blocking. In section 2, the various techniques used to study the event are presented in some detail. Section 3 contains a general analysis of the planetary-scale environment out of which the event formed and the main results of the paper. The paper ends in section 4 with a brief discussion of the results.

2 Data and Methods

2.1 Data

The dataset used to examine the dynamics of this event was the NCEP/NCAR reanalyses of the standard atmospheric variables at various pressure levels: sea level pressure, zonal and meridional winds, geopotential height, and temperature. These variables were used to calculate the wave activity flux, integrated enstrophy, as well as the PV, and PV tendency on the 315 K surface.

2.2 Methods and Diagnostics

A more complete description of the the blocking definition used in this study can be found in [7]; however, it can be described as integrating both the subjective Rex criteria (see [1, 2]) and the objective Lejenas-Okland criteria, see [3], but with a minimum threshold of persistence of five days. This definition was used to detect the blocking onset and decay times for the event considered in this study.

The potential vorticity (PV) was calculated on the 315 K surface:

$$\mathrm{PV} = \rho^{-1} \boldsymbol{\zeta}_a \cdot \nabla\theta,$$

where $\boldsymbol{\zeta}_a$ is absolute vorticity, θ is the potential temperature. The change in block center point PV was calculated using the method outlined in [8]. As described there, the development of a blocking event is described by the advection of PV,

$$\frac{\partial \mathrm{PV}}{\partial t} = -\mathbf{v}_h \cdot \nabla \mathrm{PV}.$$

The respective roles of the synoptic-scale and planetary-scale forcings may be a examined by the methodology of [8, 9]. The scales were obtained by substituting $\mathrm{PV} = \overline{\mathrm{PV}} + \mathrm{PV}'$ into the above tendency equation where the overbar (prime) denotes the planetary-scale (synoptic-scale) component, to get

$$\frac{\partial \mathrm{PV}}{\partial t} = \left.\frac{\partial \mathrm{PV}}{\partial t}\right|_P + \left.\frac{\partial \mathrm{PV}}{\partial t}\right|_S + \left.\frac{\partial \mathrm{PV}}{\partial t}\right|_I = P + S + I,$$

where P, S, I, represent the planetary, synoptic, and scale interaction PV advections respectively where I represents nonlinear interactions. To separate the planetary-scale wavelengths from the synoptic-scale wavelengths a second order Shuman filter was used.

The 500 hPa geopotential heights Z were also filtered with a Shuman filter to retain the planetary-scale waves ($\geq$ 6000 km). The synoptic-scale heights were calculated as a residual: $Z_s = Z - Z_p$. Following the method of [13] the planetary-scale height field was averaged over a 40° latitude by 60° longitude box encompassing the block domain. Plots of Z_p and Z_s were then used to determine the scale dominance of the blocking event: planetary-scale, synoptic-scale, alternating, where as explained in [13] these represent three classes of solutions of the nonlinear barotropic vorticity equation. The heights were compared to their monthly averages to determine scale dominance. If the planetary-scale (synoptic-scale) heights in the block domain aren't greater than the monthly average of the planetary-scale (synoptic-scale) heights throughout the duration of the block, the event is classified as alternating.

As noted in [15] the planetary-scale flow in midlattitudes has cyclic regimes. These regimes arise from the propagation and dispersion of Rossby waves. Phase diagrams can used to effectively display these cyclic regimes, [15]. To determine the evolution dynamics of block formation and maintenance, trajectories of a variable X can be plotted in the phase plane, where the horizontal coordinate is X and the vertical coordinate is dX/dt. In this study the trajectories of X =geopotential height were analyzed by calculating dX/dt with 4th-order finite differencing truncation in a 40° by 60° box for the duration of the blocking event. In this ideal autonomous case, for cyclic regimes, the trajectories correspond to a harmonic oscillator and are circular. For stable regimes, trajectories approach a limit cycle. For this reason, the phase diagram is suitable to determine regime changes. Since the system is non-autonomous the attractor regime may change its character and the trajectories may cross.

A series of recent studies (see [16] and the references therein) have demonstrated that enstrophy may be used as an indicator of the stability of large-scale flows. Enstrophy based diagnostics have been used to identify the change in flow regimes, especially the onset and decay periods for blocking. The diagnostic used here is the domain integrated enstrophy (IRE):

$$\mathrm{IRE} \equiv \int \zeta^2 \mathrm{d}A,$$

where the area A over which the integral is evaluated can be an entire hemisphere, or the blocking domain, such as a 40 by 60 degree box around the blocking event, [13]. Relative maxima in the IRE time series in the blocking domain under consideration represent increased instability and correlate well with block onset and decay, while during the maintenance phase of a block, the IRE dips to a minimum. The instability indicated by the IRE is correlated with the sum of the positive finite-time Lyapunov exponents, [14].

3 Synoptic and Dynamic Analysis

3.1 Synoptic- and Planetary-scale Analysis

The event considered here occurred from January 23-February 16, 2014 and was centered at 130 W. This blocking event developed from an anomalously strong ridge over the west coast of the United States. In this section the environment in which the blocked formed and was maintained will be discussed.

In January (for details see National Climatic Data Center, State of the climate: Synoptic discussion for January 2014, http://www.ncdc.noaa.gov/sotc/synoptic/2014/1) positive SST anomalies grew more extensive in the North Pacific, while the East Pacific-North Pacific pattern index (EP-NP) was positive. The Pacific North American pattern index was also positive during January. However, the circulation and temperature patterns during January resembled the EP-NP pattern more than the PNA pattern as noted by the NCDC and can be seen in seen in the geopotential height and temperature fields (not shown). Both the SSTs and the circulation pattern contributed to the ridging over the west coast from which the blocking event formed.

February was somewhat different, (for details see National Climatic Data Center, State of the climate: Synoptic discussion for January 2014, http://www.ncdc.noaa.gov/sotc/synoptic/2014/2). The NCDC notes that there was no teleconnection pattern that captured the circulation completely. However, the EP-NP pattern continued positive, while, the PNA pattern changed from positive to negative in the first part of the month, indicating that there was a change in the flow regime. This can be seen in figure 1, where a clear shift in the alternating pattern of positive/negative height anomalies from January has occurred, i.e., the jet has shifted. As noted in the introduction, blocking events are expected to decay in the event of such a change. However, as will be shown in the next subsection, the blocking event was maintained in spite of the large-scale flow regime change. Additional evidence for the change will be presented in the next section. Also, the SSTs in the blocking region become anomalously strong during the early part of February (not shown) likely contributing to the maintenance of the blocking event.

This blocking event that formed under the influence of the described conditions was a long-lived and large amplitude event. According to the blocking event archive at http://solberg.snr.missouri.edu/gcc/ it is the 11th strongest Northern Hemisphere event lasting longer than 20 days since 1968 as measured by

Phase	Time Period
Onset	January 21-22
Intensification	January 23-25
Maintenance 1	January 26-February 2
Intensification 2	February 3-6
Maintenance 2	February 7-10
Intensification 3	February 11-13
Decay	February 14-16

Table 1: Time periods of the blocking event partitioned using the BI.

its Block Intensity index (BI) of 5.93. Block intensity is defined as $\mathrm{BI} = 100\,[(Z_{max}/Z) - 1]$. Here Z_{max} is the maximum 500 hPa height in the closed anticyclone region or on a line associated with the ridge, and Z is the subjectively chosen 500 hPa height contour encompassing the upstream and downstream troughs, see [7] for a more thorough explanation. The BI measures the amplitude of the quasi-stationary wave in the blocking region. The BI was calculated daily during the event, see figure 2. The BI was used to partition the blocking event into different phases, as in [8], see table 1, which will be used below in the PV tendency calculations.

3.2 Dynamic Analysis

a) General description of the event: As described in [12], the ridge out of which the blocking event originated was in part formed by wave-activity fluxes from the subtropical Pacific. The formation of the ridge over the west coast of the United States was examined using the Rossby wave activity-flux, defined by Takaya et al. [17] for the prediction of propagating planetary waves in mean flows. Additionally, [17] demonstrates that the absorption of Rossby wave packets is instrumental in the formation of blocking. As can be seen in figure 3, a persistent source of Rossby wave energy was absorbed in the Gulf of Alaska in January-February throughout the event thus sustaining it. Moreover, Rossby wave energy originated there and propagated to the eastern US possibly contributing to the extreme cold temperatures there, [12].

This event followed the [4] Tsou and Smith conceptual model in its formation, which specifies that a blocking event forms when the following ingredients are in phase: i) A planetary-scale quasi-stationary 500 hPa ridge, ii) A developing precursor upstream surface cyclone, iii) An associated amplifying 500 hPa upstream short-wave ridge, iv) Strong jet maximum.

As described above, a strong quasi-stationary planetary-scale ridge over the West Coast of the United States was present, see [12] for a more thorough description. As described in [4], blocking events are preceded by upstream surface cyclogenesis. In this event, there was a deep (966 mb at one point) cyclone that abutted the ridge by the 20th of January, three days before the ridge became a blocking event. Along with that there was an amplifying 500 hPa upstream short-wave ridge that can be described by processes explained below. Finally, the strong jet maximum imparted anticyclonic vorticity to the blocking region.

By the 4th of February a strong positive 500 hPa height anomaly (long-wave ridge) was building in the Western Pacific (see figure 4), while the original event was moving westward. By the 6th these two ridges merge to restrengthen the blocking event. This merger was accompanied by significant positive SST anomalies as well (not shown). Finally, the event dissipated as strong cyclogenesis entered the region and an upper level trough finally eroded the blocking ridge by mid-February.

b) Height scale-partitioning: The method used to filter and partition the geopotential heights into planetary- and synoptic-scales was reviewed in section 2.2. The scale partitioned heights were compared to their monthly averages in January and February as in [13]. The planetary-scale heights (see figure 5) are above their monthly average in the blocking domain until approximately February 7th and then remain below the average for the rest of the duration of the blocking event, indicating that planetary-scale processes may have had a significant role in the preconditioning and onset dynamics of the event. Figure 5 also shows the loss of support by the planetary-scale that led to the decay of the event. The synoptic-scale heights are initially above their monthly average (corresponding to the amplifying 500 hPa short-wave ridge in the Tsou and Smith model), but soon decrease below the average. Near February 7th the synoptic-

Phase	Planetary-scale PV	Synoptic-scale PV	Interaction PV
Onset	1.06	0.008	0.06
Intensification	0.82	-0.018	-0.028
Maintenance 1	3.005	-0.044	-0.99
Intensification 2	0.82	-0.048	0.39
Maintenance 2	-2.2	-0.058	-0.98
Intensification 3	9.62	-0.17	0.48
Decay	13.024	0.019	5.13

Table 2: Scale Partitioned PV Tendency on 315 K Surface: $\mathrm{PV} \times \mathrm{PVU\ day}^{-1},\ 1\mathrm{PVU} \equiv 10^{-6}\mathrm{Km}^2\mathrm{kg}^{-1}\mathrm{s}^{-1}$.

scale heights begin to rise near the average and soon exceed it (see figure 6) before finally dipping below the average at block decay. This event can be classified as an alternating scale event as in [13] since neither the planetary nor synoptic scale was above its monthly average throughout the duration of the event. This indicates that both scales play important roles in the formation (both contribute positively) and maintenance of the event (planetary-scale loses support, synoptic-scale contributes positively). The loss of support of the planetary-scale and the gain in support of the synoptic-scale around February 7th coincides with a marked increase in the BI (see figure 5 and section 3.1).

c) Phase diagram: The method of calculation and use of phase diagrams was explained briefly in section 2.2. For the phase diagram used here trajectories of planetary-scale heights during the blocking event were plotted, see figure 7: Z_p (planetary-scale height) vs. dZ_p/dt in a 40° by 60° box. The trajectory in the blocking domain quickly goes into a limit cycle, representing a stable regime. Around February 6-7 the trajectory leaves the first limit cycle which corresponds to a change in planetary-scale flow regime. The trajectory goes into another small limit cycle before the event finally decays.

d) IRE: As described in section 2.2, enstrophy and enstrophy based relationships can be used as indicators of the stability of large-scale flows. These quantities can be used to identify the change in flow regimes, including the onset and decay periods for blocking events. The past research has shown that block onset and decay are associated with relative maxima in the enstrophy time series. Typically, during the maintenance phase of a blocking event, the enstrophy dips to a relative minimum. the IRE time series for this event is shown in figure 8. The IRE reaches a relative maximum near onset and rises to another relative maximum at block decay, indicating increased instability as described in section 2.2. The IRE then dips to a relative minimum. However, near February 7th, the IRE rises to a significant maximum, indicating a change in the planetary-scale dynamics. This along with the shift in the pattern of high/low in the height field which can be seen in figures 1 and 4 and in the PNA pattern index change from positive to negative, lend evidence to the change in the flow regime.

e) PV: The potential vorticity (PV) tendency was calculated as explained in section 2.2. The filtered PV tendencies were calculated at the blocking center point and time averaged for specific time periods during the blocking event, see tables 1 and 2. The synoptic-scale tendency is mainly supportive of negative PV advection in the blocking region except at onset and decay, while the interaction PV alternates signs. The planetary-scale PV is mostly positive, suggesting that it doesn't have as significant a role in maintaining the block. However, during the Maintenance period 2 (see tables 1 and 2), all three scales play a significant role in the maintenance of the blocking event, implying that the interaction between scales is nonlinear (see [8]). As discussed above, the blocking ridge merges with another developing ridge during this time. Also, as seen in figure 9 the cyclonic PV streamer may have played a role in sustaining the block by the diabatic depletion of PV at upper levels [18]. The location of the cyclonic PV streamer corresponds with the trough to the east seen in figure 4. There is cyclogenesis in the central Pacific between the blocking ridge and the developing ridge in the western Pacific, as represented in the figure by the cyclonic PV streamer, which eventually becomes the eastern part of the omega block.

4 Discussion and Conclusions

This long-lived event (January 23-February 16, 2014) formed out of the ridge over the West Coast of the United States associated with severe drought conditions in California that has been shown to have an anthropogenic footprint, see [12]. The EP-NP pattern index was positive, indicating there was a favorable environment for the block to form. Moreover, as explained in [12] and as seen in figure 2, Rossby wave energy dispersed downstream of the event which deepened the trough over the northeastern part North America. This led to plunging temperatures and the "polar vortex". Additionally, this event was the 11th strongest of the events that lasted longer than 20 days, see http://solberg.snr.missouri.edu/gcc/.

Several techniques were employed in the study of the dynamics of this event. Some of the techniques used here aren't as aren't as well known in the literature on blocking, but are effective at illustrating the exceptional nature of this event as it survived a regime change. A potential weakness in all of the techniques employed here is that they tend to emphasize the 500 hPa surface dynamics, somewhat arbitrarily, see [6]. Also, the temperature advection and other thermodynamic variables aren't taken into account either. However, the techniques used here give a reasonably comprehensive view of the dynamics of the event, especially the changing nature of the flow in early February.

The suggestion in [8, 11] that blocking events may not survive an abrupt transition from one planetary-scale flow regime to another is here shown to be not entirely correct. The event under consideration here was a strong event that survived a large-scale change in flow regimes as evidenced by the changes in PNA pattern index, the height pattern as seen in figure 1, the phase diagram and the IRE. The nonlinear interaction as evidenced by the PV in table 2 and the merger between the two ridges shown in figures 4 and 10 sustained the blocking event in the face of potential dissipation. Thus, fortuitous synergistic nonlinear interaction may have increased the persistence in the face of regime change.

References

[1] D.F. Rex, "Blocking Action in the Middle Troposphere and its Effect on Regional Climate I: The Climatology of Blocking Action," *Tellus*, vol. 2, 196-211, 1950a.

[2] F. Rex, "Blocking Action in the Middle Troposphere and its Effect on Regional Climate II: The Climatology of Blocking Action," *Tellus*, vol. 3, 275-301, 1950b.

[3] H. Lejenas and H. Okland, "Characteristics of Northern Hemisphere Blocking as Determined from a Long Time Series of Observational Data," *Tellus*, vol. 35A, 350-362, 1983.

[4] C.H. Tsou and P.J. Smith, "The role of synoptic/planetary-scale interactions during the development of a blocking anticyclone," *Tellus*, vol. 42A, 174-193, 1990.

[5] C. Schwierz, M. Croci-Maspoli, and H.C. Davies, "Perspicacious indicators of atmospheric blocking," *Geophys. Res. Lett.*, vol. 31, L06125, doi:10.1029/2003GL019341, 2004.

[6] D. Small, E. Atallah, and J.R. Gyakum, "An Objectively Determined Blocking Index and its Northern Hemisphere Climatology," *J. Climate*, vol. 27, 2948-2970, 2013.

[7] J.M. Wiedenmann, A.R. Lupo, I.I. Mokhov, and E. Tikhonova, "The climatology of blocking anticyclones for the Northern and Southern Hemispheres: Block intensity as a diagnostic," *J. Climate*, vol. 15, 3459-3473, 2002.

[8] J.P. Burkhardt and A.R. Lupo,"The Planetary- and Synoptic-Scale Interactions in a Southeast Pacific Blocking Episode Using PV Diagnostics," *J. Atmos. Sci.*, vol. 62, 1901-1916, 2005.

[9] S.J. Colucci, "Planetary-scale preconditioning for the onset of blocking," *J. Atmos. Sci.*, vol. 44, 124-139, 2001.

[10] H. Nakamura, M. Nakamura, and J.L. Anderson, "The role of high and low frequency dynamics and blocking formation," *Mon. Wea. Rev.*, vol. 125, 2074-2093, 1997.

[11] K. Haines and A.J. Holland, "Vacillation cycles and blocking in a channel," *Q.J.R. Meteorol. Soc.*, vol. 124, 873-897, 1998.

[12] S.-Y. Wang, L. Hipps, R.R. Gillies, and J.-H. Yoon, "Probable causes of the abnormal ridge accompanying the 2013-2014 California drought: ENSO precursor and anthropogenic warming footprint," *Gephys. Res. Lett.*, vol. 41, 3220-3226, 2014.

[13] H. Athar and A.R. Lupo, "Scale and stability analysis of blocking events from 2002-2004: A case study of an unusually persistent blocking event leading to a heat wave in the Gulf of Alaska during August 2004," *Advances in Meteorology* vol. 2010, Article ID 610263, 15 pages, 2010.

[14] V.P. Dymnikov, Y.V. Kazantsev, and V.V. Kharin, "Information Entropy and Local Lyapunov Exponents of Barotropic Atmospheric Circulation," *Izv. Atmos. Oceanic Phys.*, vol. 28, 425-432, 1992.

[15] A.R. Lupo, I.I. Mokhov, S. Dostoglou, A.R. Kunz, and J.P. Burkhardt, "The impact of the planetary scale on the decay of blocking and the use of phase diagrams and enstrophy as a diagnostic," *Izv. Atmos. Oceanic Phys.*, vol. 42, 45-51, 2007.

[16] A.D. Jensen and A.R. Lupo, "Using Enstrophy as a Diagnostic to Identify Blocking Regime Transition," *Q.J.R. Meteorol. Soc.*, vol. 682, 1677-1683, 2014.

[17] K. Takaya and H. Nakamura, "A Formulation of a Phase-Independent Wave-Activity Flux for Stationary and Migratory Quasigeostrophic Eddies on a Zonally Varying Basic Flow," *J. Atmos. Sci.*, vol. 58, 608-627, 2001.

[18] R.W. Moore, O. Martius, and T. Spengler, "The Modulation of the Subtropical and Extratropical Atmosphere in the Pacific Basin in Response to the Madden–Julian Oscillation," *Mon. Wea. Rev.*, vol. 138, 2761-2779 , 2010.

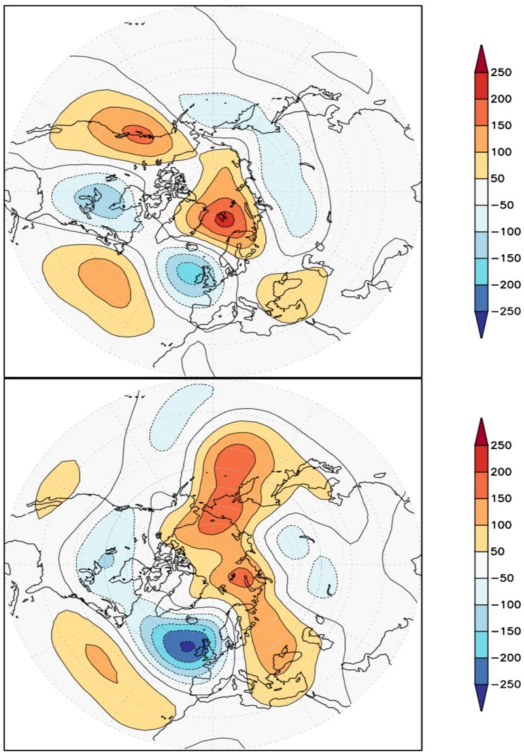

Figure 1: Top: January 2014 geopotential height anomalies. Bottom: February 2014 geopotential height anomalies.

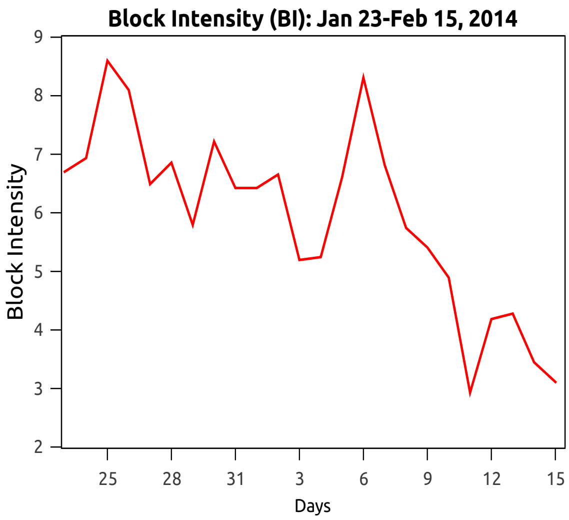

Figure 2: Block intensity as a function of time: January 21-February 15, 2014.

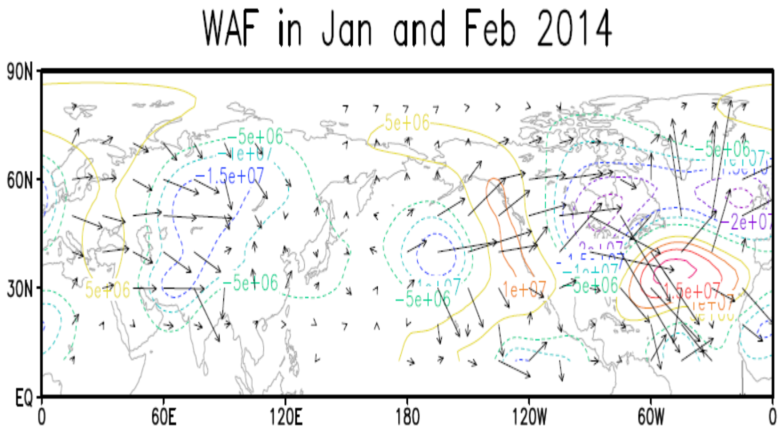

Figure 3: Rossby Wave Activity Flux in January and February 2014.

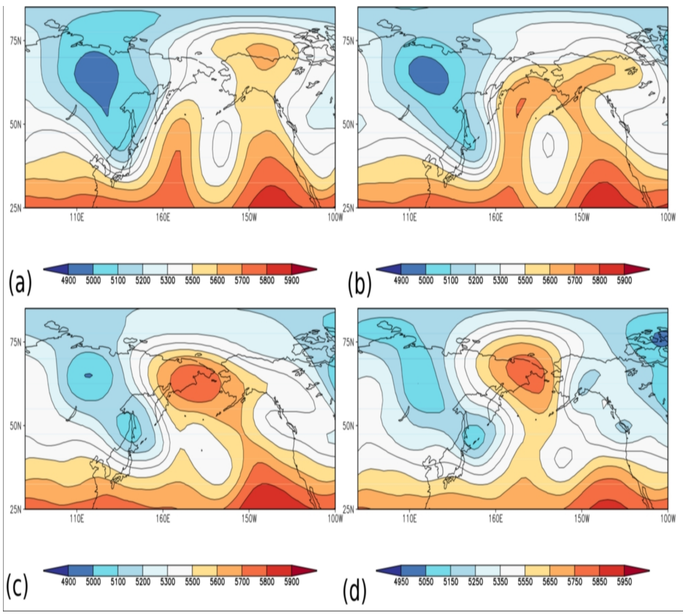

Figure 4: Upstream 500 hPa ridge merging with the block: (a) Feb. 4th, (b) Feb. 5th, (c) Feb. 6th, (d) Feb. 7th.

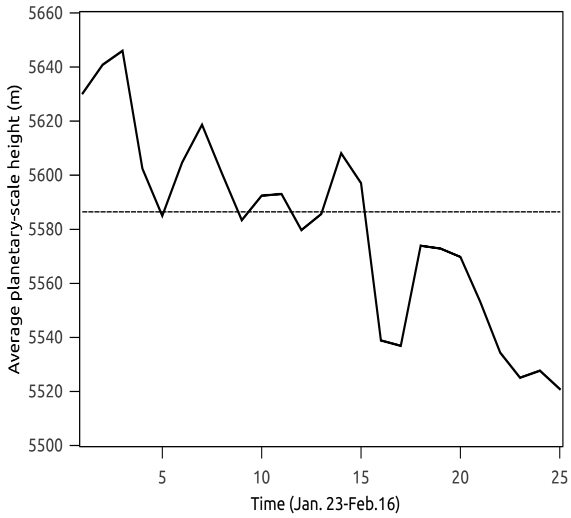

Figure 5: Planetary-scale 500 hPa geopotential heights for January 23 - February 16. The horizontal line represents monthly mean.

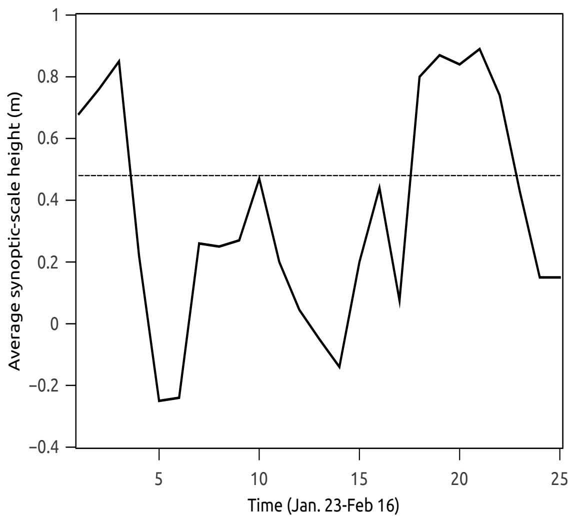

Figure 6: Synoptic-scale 500 hPa geopotential heights for January 23 - February 16. The horizontal line represents monthly mean.

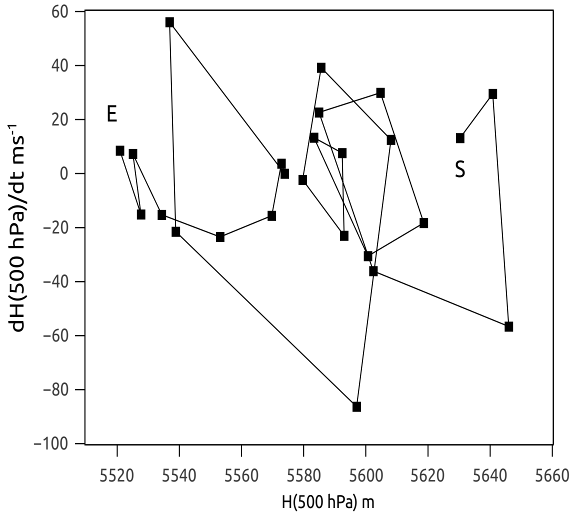

Figure 7: Phase diagram of 500 hPa planetary-scale heights for January 23 - February 16. Each point represents a day. S=start, E=end.

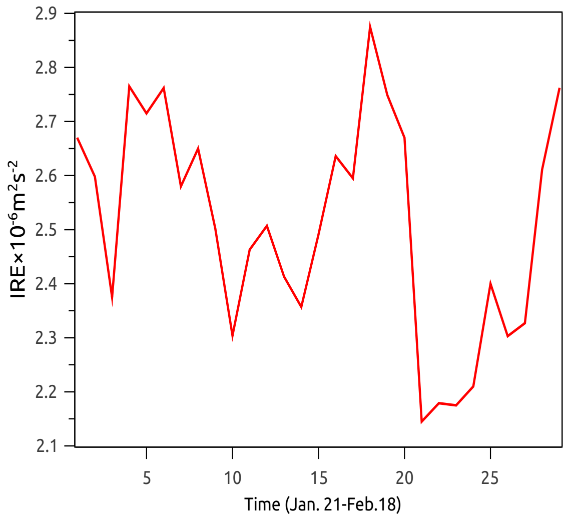

Figure 8: Integrated enstrophy (IRE) for January 23 - February 16.

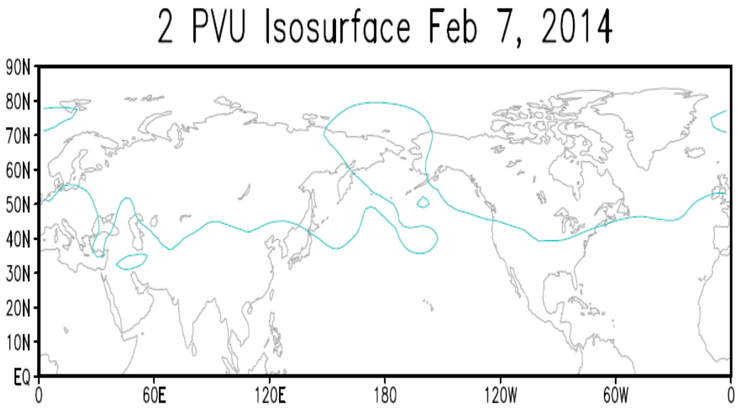

Figure 9: 2 PVU surface for February 7, 2014.