AN ANALYSIS OF NORTHERN HEMISPHERE BLOCK SIZES COMPARED TO CLIMATOLOGY AND SEASONAL VARIATIONS

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by
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ABSTRACT

The goal of the following research was to discover if any trends exist between the size of large-scale, mid-latitude anticyclonic events and seasonal characteristics. A 20-year analysis of North American blocking events was compiled by calculating the mean size of each event using NCEP-NCAR analyses and a simplified Rossby wave equation. Blocking events were identified using block definitions from previous studies and retrieved from the University of Missouri-Columbia blocking database. The sizes of blocking events were then compared to Northern Hemisphere climatological information derived in previous research. Block sizes were compared to El Niño-Southern Oscillation, blocking intensity as defined by Wiedenmann et al. 2002, and other seasonal characteristics. Results will assist researchers and long-range forecasters to predict the scale and potential impacts of blocking events, of which onset and duration are currently difficult to forecast.

INTRODUCTION

1.1 – BLOCKING FORMATION

The definition of blocking anticyclones varies between publications. In general they are large-scale, mid-latitude atmospheric occurrences. While large-scale, blocking events are considered to be local phenomena (Lejenas and Okland 1983, Lupo 1997, and Fournier 2000), the relationship between synoptic forcing and blocking events has been found to be pivotal for the onset and persistence of events. Tsou and Smith (1990) and Lupo and Smith (1998) both demonstrated the importance of synoptic- and planetary-scale forcing on blocking events in the Northern Hemisphere. They found a relationship existed between blocks and pre-existing upstream cyclones, aided by jet steaks. The studies concluded that jet streaks strengthened with response to blocking events and that the jet streak led to anticyclonic vorticity advection, which resulted in the amplification of the surface ridge.

Several studies have shown the roles of synoptic-scale forcing and planetary-scale flow on blocking formation and maintenance (Tsou and Smith 1990, Lupo and Smith 1995b, and Lupo 1997). Generally, the development of a synoptic-scale cyclone upstream of a large-scale ridge creates an area favorable for blocking formation. While the cyclone is developing due to dynamic forcing, namely vorticity advection, the relationship between cyclone development and the ridging downstream intensifies. This in turn leads to the onset and strengthening of a blocking event due to anticyclonic vorticity. Lupo and Smith (1995b) provided a thorough analysis of a singular Northern Atlantic blocking event in October-November 1985. They concluded that upper tropospheric anticyclonic vorticity advection was the single most important factor to block formation and maintenance, while adiabatic warming, vorticity tilting and jet streak amplification aided the formation.

Location of blocking formation has also been studied extensively (Rex 1950, Treidl et al. 1981, and Lejenas and Okland 1983) indicating favored formation regions over the eastern Atlantic and Pacific oceans, downstream from the storm tracks over North American and Asian continents. Dole and Gordon (1983) were among the first to identify eastern Europe/western Asia as a third distinct area of formation apart from the Pacific and Atlantic basins (and later supported in Lupo and Smith 1995a). This area of formation is downstream from a storm track that traverses the northern Mediterranean Sea (Whittaker and Horn 1982). Lupo and Smith (1995a) showed the preferred longitudes of preferred blocking events to be between 160°E and 130°W in the Pacific, 10°W over the eastern Atlantic and near 40°E over the eastern Europe continent. In relation to latitude, more blocks concentrate between a band stretching from 60° to 70°N, with events over the Atlantic-European region occurring southward to 60°N while Pacific events formed poleward of 60°N (Barriopedro et al. 2006).

1.2 – BLOCKING CHARACTERISTICS

Extensive research has been conducted to better understand climatological characteristics of blocking events, including the aforementioned formation regions, duration, frequency, blocking days and intensity (Triedl et al. 1981, Dole and Gordon 1983, Lejenas and Okland 1983, Lupo and Smith 1995a, Wiedenmann et al. 2002, Barriopedro et al. 2006). Numerous studies showed that blocking events occur most frequently during the cold season (October-April) and that events are both stronger and more persistent during that time (Lupo and Smith 1995a and Wiedenmann et al. 2002). Further, cold season and oceanic region blocking events are stronger than warm season or continental blocking events (Dole and Gordon 1983). More specifically, Mokhov et al. (2001) concluded that Atlantic Ocean events were more persistent, while the strongest events occurred in the Pacific Ocean basin.

Blocking events are found to occur quite frequently in the Northern Hemisphere where the average annual number of events ranged from 21 (Triedl et al. 1981, Lejenas and Okland 1983, Lupo and Smith 1995a), 25 (Wiedenmann et al. 2002) and to 27 (Barriopedro et al. 2006). Event frequency was greater in the winter (January-March) and fall (October-December) seasons, and less in the spring (April-June) and summer (July-September) seasons (Lupo and Smith 1995a). While there were slight variations in seasonality of blocking frequency maxima and minima, Lupo and Smith (1995a) concluded that in general, blocking most frequently occurred in the winter season and less frequently in the summer season over the Atlantic and Pacific basins. Of note however, is that there was little to no seasonal variation for blocks over the Continental regions.

The total number of blocked days in the Northern Hemisphere was discussed in

Lupo and Smith (1995a). Blocked days refer to the difference between the sum of the three regions (Atlantic, Pacific, and Continental) and the number of days when simultaneous blocking occurred. The average number of blocking and simultaneous blocking days for each year in their study was 170.5 and 31.9. Thus, as stated in Wiedenmann et al. (2002) and previously discussed in Lejenas and Okland (1983), blocking events were present on 46.7% of the days in a year and 8.7% of the days in a year had simultaneous events occurring. That is, on average, nearly half the days in a year are blocked (a statistic later supported in Barriopedro et al. 2006). Rex (1950), Quiroz (1987), and Lupo and Smith (1995a) documented that the strongest blocking events occurred simultaneously with another event. Wiedenmann et al. (2002) noted that 9 of the 10 strongest blocks occurred simultaneously with another block in the Northern Hemisphere. Both were shown to be stronger than the 30-year mean intensity.

The average duration of blocking events was found to be 8.6 days (Lupo and Smith 1995a). The study showed that events over the Atlantic basin and Continental region were slightly more persistent than Pacific, and that most events lasted between 5 and 7 days, then decreasing significantly for events with a duration greater than 10 days. Winter season events in the Atlantic and Pacific blocking regions were longer-lived, lasting an average of 11.0 and 8.6 days. Continental blocking events did not have a significant difference in average durations between seasons, except for a slight increase during the fall. However, the authors state this data may be skewed due to a single blocking event that lasted for 25 days.

Blocking intensities have also been studied (Lupo and Smith 1995a and Wiedenmann et al. 2002). Wiedenmann et al. (2002) concluded that Northern Hemisphere events had an average BI of 3.15 and that Atlantic events (3.37) had a higher BI compared to events in the Pacific and Continental regions (3.14 and 2.63, respectively). This conclusion supported the results of Lupo and Smith (1995a), which indicated similar comparisons between intensities and formation regions.

1.3 – INTERANNUAL VARIABILITY

The relationship between El Niño-Southern Oscillation and atmospheric blocking has been broadly explored in recent years (Renwick and Wallace 1996, Mokhov and Tikhonova 2000, Watson and Colucci 2002, and Barriopedro et al. 2006). Wiedenmann et al. (2002) provided a rich source of climatological data for Northern Hemisphere anticyclones pertaining to ENSO. In general, it was discovered that Northern Hemisphere blocking events were stronger and more frequent during La Niña years, compared to Southern Hemisphere events, which were stronger and more frequent during El Niño years. Focusing on continental events, there was more blocking in La Niña and neutral years, a result supported by Mokhov and Tikhonova (2000).

During Wiedenmann et al. (2002)'s examination of NH blocking days and durations, numerous comparisons were made. For the entire hemisphere, La Niña years had an increase in the number of days, but not duration. Regionally, the Atlantic and Continental regions showed a decrease in duration with no apparent change in the number of days. There was an increase in the number of events in the Pacific, leading to an increase in the number of days and duration of events.

While researchers concluded there is no apparent statistical trend in the annual occurrence of blocking, the annual variations of blocking duration and intensities were similar (Wiedenmann et al. 2002). During cold season events, blocking events were longer-lived and stronger than warm season events in each ENSO phase (Wiedenmann et al. 2002). Specifically, events in the NH were stronger during La Niña and neutral years than El Niño years (Barriopedro et al. 2006). This result is supported by Renwick and Wallace (1996), who focused solely on the cold season Northern Hemispheric Pacific region and showed that blocking was suppressed in El Niño years.

As mentioned earlier, cyclonic formation at the surface has been shown to influence blocking formation (Lupo and Smith 1995b). Provided with that connection, an increase in cyclonic activity during ENSO would likely lead to higher frequencies of blocking events (Wiedenmann et al. 2002). The increase in Northern Hemisphere blocking events during La Niña corresponded with an increase in cyclones (Key and Chan 1999). While the current study will focus on the Northern Hemisphere characteristics, similar results were found to be true in the Southern Hemisphere; that is, more active Southern Hemisphere Pacific region corresponded with an increase in activity in the Southern Hemisphere midlatitudes.

Beyond ENSO connections, longer variability patterns have recently been explored concluding that at annual scales, there was no significant influence on regional blocking (Barriopedro et al. 2006). However, several patterns were noticed during cold seasons, mainly the North Atlantic Oscillation (NAO). During the negative phase of the NAO, the number of Atlantic region blocking days during winter (fall) was 31.7 (21.1) compared to the positive phase of the NAO, which was 12.7 (9.2). Also during the negative phase, winter blocking events lasted more than 11 days on average, up from 8 during the positive phase. These results are similar to those of Shabbar et al. (2001), who showed a significant increase in the number of blocking days and lifetime of blocking events during a negative NAO. Other patterns were found during Scandinavia (SCAN) variability, which showed average annual frequencies of blocked days were doubled and more persistent during a positive winter phase over Europe, and during the East Pacific (EP) variability, where negative phases led to 24.1 average winter blocked days (versus 8.6 for a positive phase).

While Lupo and Smith (1995a) were able to show connections between blocking sizes and seasonal variability, their data was limited to a three-year range. The current study includes a larger data sample beginning January 1992 and ending December 2011. In total, 669 Northern Hemisphere blocking events were studied in the 20-year range. The objectives of the following research were to show the correlation between blocking events sizes and seasonal and interannual variability, including El Niño-Southern Oscillation.

DATA AND METHODOLOGY

2.1 – DATA

Data used in this study were retrieved from the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) gridded reanalyses data located in Boulder, Colorado. The 0000 and 1200 UTC (further known as 00Z and 12Z for Universal Coordinated Time) NCEP-NCAR reanalyses are used here for calculations, but they are available at six-hour intervals on grids of 2.5° latitude X 2.5° longitude. All NCEP-NCAR data were gathered from the following website: http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.pressure.html

To locate blocking events and calculate block sizes, 500-hPa gridded heights were used. Blocking events were identified from the University of Missouri-Columbia archive of Northern and Southern Hemisphere events. Those events can be found at: http://weather.missouri.edu/gcc. The archive includes complete data on timing and location, and blocking intensity as defined by Weidenmann et al. (2002) and previously by Lupo and Smith (1995a).

Table 1: Regional domains, longitudes and seasons used in this research.
(Adapted from Wiedenmann et al. 2002)

Season	**Months (NH)**	**Regional domain**	**Longitudinal boundaries (NH)**
Summer	Jul – Sep		
Autumn	Oct – Dec	Atlantic	80°W – 40°E
Winter	Jan – Mar	Pacific	140°E – 100°W
Spring	Apr - Jun	Continental	100°-80°W and 40°E – 140°E

Table 2: Regional and seasonal distribution of blocking events 1992-2011.

Region	Summer	Autumn	Winter	Spring	Total
Atlantic	58	75	82	73	288
Pacific	35	46	71	59	211
Continental	58	25	29	58	170
All events	151	146	182	190	669

2.2 METHODOLOGY

Data analyses and procedures for calculating block sizes for this thesis project were carried out using Microsoft Excel and manual calculations of each blocking event. Manual calculations allowed visual confirmation of each blocking event that occurred in the 20-year period. Using the data from the blocking archive, the timing (both onset and termination), duration, hemispheric location (Atlantic, Pacific, Continental) and longitude of onset of Northern Hemisphere blocking events were recorded. Blocking events were then plotted once daily for the duration of the event on 500 hPa height charts from 20°N to 90°N. For cases in which an event lasted for an additional half day, the half day was counted as a full day.

Blocking events were chosen from the University of Missouri-Columbia database (http://weather.missouri.edu/gcc). Those events were previously classified as blocking events using the definition found in Lupo and Smith (1995):

a) The criteria in Rex (1950) must be satisfied for an anticyclone flow region at 500 mb with the exception that the minimum duration must be 5 days (Triedl et al. 1981) and the anticyclonic region must extended over 30° longitude (Lejenas and Oakland 1983).

b) A negative or small positive Lejenas-Oakland (LO) index must be present on the Hovmoller diagram(s).

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

d) The anticyclone should be north of 35°N and have amplitude of at least 5° latitude.

e) Onset occurs whenever the anticyclone satisfies criteria (d) and either (a) and (b).

f) Termination of the event occurs whenever the block fails to satisfy criteria (d) and either (a) or (b) for 24 hours.

To calculate the size of a blocking event at each daily interval, the location of an event was mapped using 500 hPa geopotential heights, with contour intervals of 60 hPa. A particular contour value surrounding the blocking event was chosen following guidelines from Lupo and Smith (1995a), which stated the height contour:

1) Must represent a full wave length, between trough lines of the upstream and downstream trough.

2) May not be a closed contour.

3) Is the middle contour of all the open contours along the wavelength (or if there is more than one contour meeting the criteria, the contour with the highest value is chosen).

Using the chosen contour, the half-wavelength of the blocking event was determined. That half-wavelength is defined as the distance between the upstream and downstream inflection points on the ridging contour (Lupo and

Smith 1995a). The distance in degrees between inflection points was recorded daily at the latitude of the half-wavelength.

Blocking sizes for each day of an event were then calculated using a simplified Rossby wave propagation equation:

$$1° \text{ longitude} = 111.15 \text{ km} * \cos(\text{latitude})$$

Then:

$$\text{BES} = \text{Degrees longitude} * \text{Width in degrees}$$

Where, BES is the Blocking Event Size recorded in kilometers. Then the mean size for the event was calculated and recorded. The blocking sizes were then used to make comparisons between seasonality, climatology and blocking intensity.

When comparing block sizes with interannual variability, the data collected were partitioned by phases of El Nino-Southern Oscillation (from here forward, referred to as ENSO). ENSO is most commonly defined using the Japan Meteorological Agency (JMA) index. The index monitors a 5-month running mean of sea surface temperature anomalies over the tropical Pacific with the domain of 4°S-4°N and 150°W-90°W. Should index values be 0.5°C or greater for 6 consecutive months, then an El Niño year is declared; -0.5°C or greater, a La Niña year; and all other values, a neutral year. An ENSO year as defined by the JMA begins in October and ends in September of the following year. A list of El Niño, La Niña and neutral years is shown in Table 3. The full definition can be found on the Center for Ocean and Atmospheric Prediction Studies website (http://coaps.fsu.edu/jma.shtml). Since ENSO years begin in October, the blocking event database will be shifted so that a year begins in October (fall season) and end in September (summer season) for results about interannual variability.

Table 3: A list of El Niño-Southern Oscillation years in this study divided into phases.

El Niño (EN)	Neutral (NEU)	La Niña (LN)
1997 2002 2006 2009	1992-1996 2000 2001 2003-2005 2008	1998 1999 2007 2010

This study then performed simple statistical analysis on the findings to obtain results that are relevant and significant. Statistical analysis was used to compare mean blocking event sizes, the annual number of events and their increase over the 20-year period. A one-way analysis of variance (ANOVA) was performed on the variables. Background knowledge on and the method of calculation of ANOVA can be found in any elementary statistics book, but in general, it is a standard operation for testing the significant trends between two or more means. For this study, all tests assumed a null hypothesis and that there is no prior correlation or relationship between the variables. Confidence levels of 95% or higher are considered significant.

Finally, Birk et al. 2010 was used to identify periods of significant variability within the 20-year dataset. A Fourier transformation was completed to discover cycles in block sizes and ENSO years. A fast Fourier transform, similar to and discussed further in Birk et al. 2010, was used to analyze 20 variables of blocking event sizes in relation to the time series. Those results will be discussed in Chapter 4.

RESULTS

3.1 CLIMATE TRENDS

The 669 blocking events analyzed from 1992-2011 were divided into graphical regions according to the domain distribution in Table 1. The total number of events in each domain (Atlantic, Pacific, and Continental) is shown in Table 2. In the 20-year period, the most events occurred in the Atlantic, with 288 blocks. The Pacific and Continental regions had fewer blocks, with 211 and 170, respectively (Figure 1).

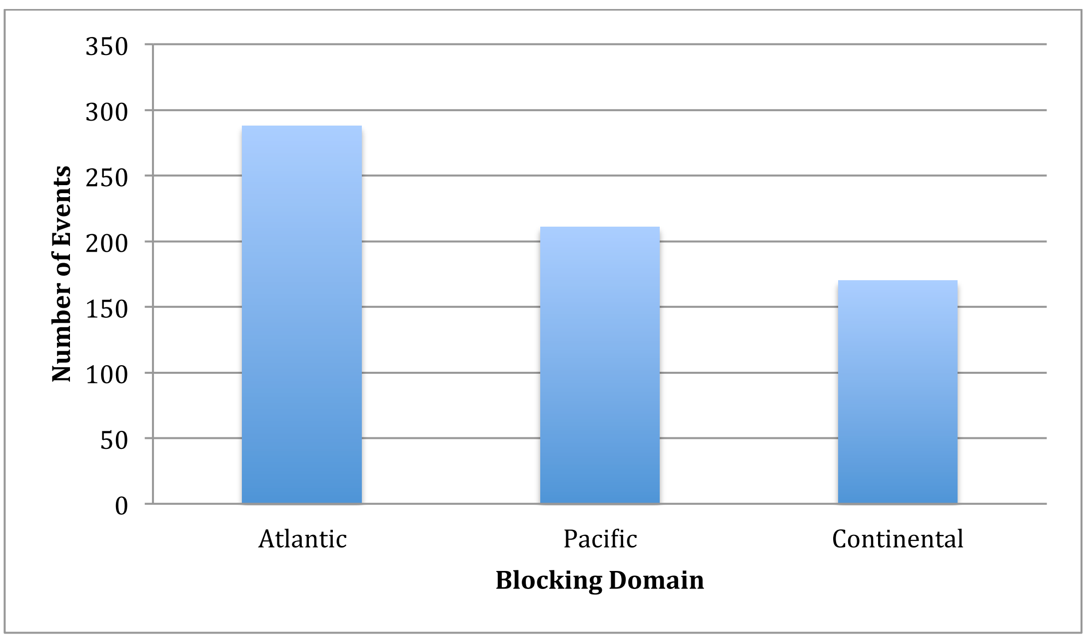

Figure 1: Total number of blocking events in each blocking domain 1992-2011.

In addition, blocks were grouped into the season of which they occurred (Figure 2). Blocking events in the Atlantic peaked during the winter with a total of 82 events. During the 20-year period, there was a gradual increase during the fall and decrease through the spring for blocking events. The Atlantic had the least amount of blocks during the warm summer months, with 58 events. Similarly, the Pacific blocking events had a maximum of 71 events during the winter and the least amount during the summer with just 35 events. These findings confirm previous results from Lupo and Smith (1995a) and Tyrlis and Hoskins (2007). Both studies showed that Northern Hemisphere blocks over the Pacific and Atlantic Ocean basins occurred more frequently during the cold season. Lupo and Smith (1995a) showed both Atlantic and Pacific events occurred most often between October and April. They attributed the location of blocks as areas downstream from primary storm tracks. Tyrlis and Hoskins (2007) showed that in the Atlantic, peak blocking activity was in the period of January-April with a noticeable minima in activity during the warmer months, July-October. In the Pacific, event maxima were in the cold season with a minimum in the summer. Continental blocking events had maxima during the warmest months of the year, in the spring and summer seasons, with 58 blocks in each timeframe. There were far fewer blocks in the cold season, with less than 30 blocks each in the autumn and winter seasons. This result supports findings from Tyrlis and Hoskins (2007), who pointed out that while blocking occurs throughout the year over Europe, there does appear to be two defined maxima over eastern Europe and Asia. The maxima occur in the summer and between January and March, while there are fewer blocks in the fall months.

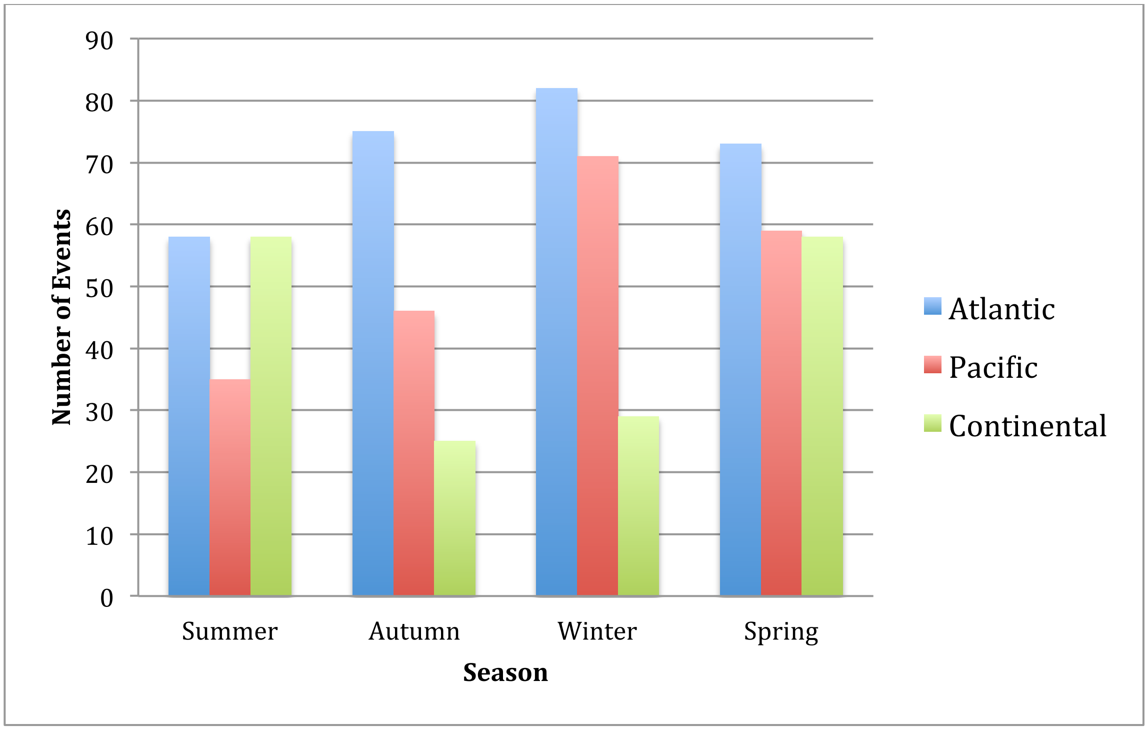

Figure 2: Total number of blocking events per season in each graphical domain.

Overall, the number of blocking events per year appears be increasing. Although the criteria for blocking events are subjective for each study, this research identified an increase in the average number of annual events in the Northern Hemisphere. Previous studies (Triedl et al. 1981, Lejenas and Okland 1983, Lupo and Smith 1995a, Wiedenmann et al. 2002 and Barriopedro et al. 2006) showed the annual average number of events to range from 21 to 27. In this study, an average of 33 events occurred each year. The annual number of events also grew linearly over the 20-year period, from 23 in 1992 to 33 in 2011 (Figure 3). The number of events in a given year peaked at 51 in 2003 and reached a low of 21 in 1998. A simple ANOVA was completed between the years and average number of blocking events. Results showed an F-score of 3.95 and P-value of 0.022. That produces significant results at the 98% confidence level.

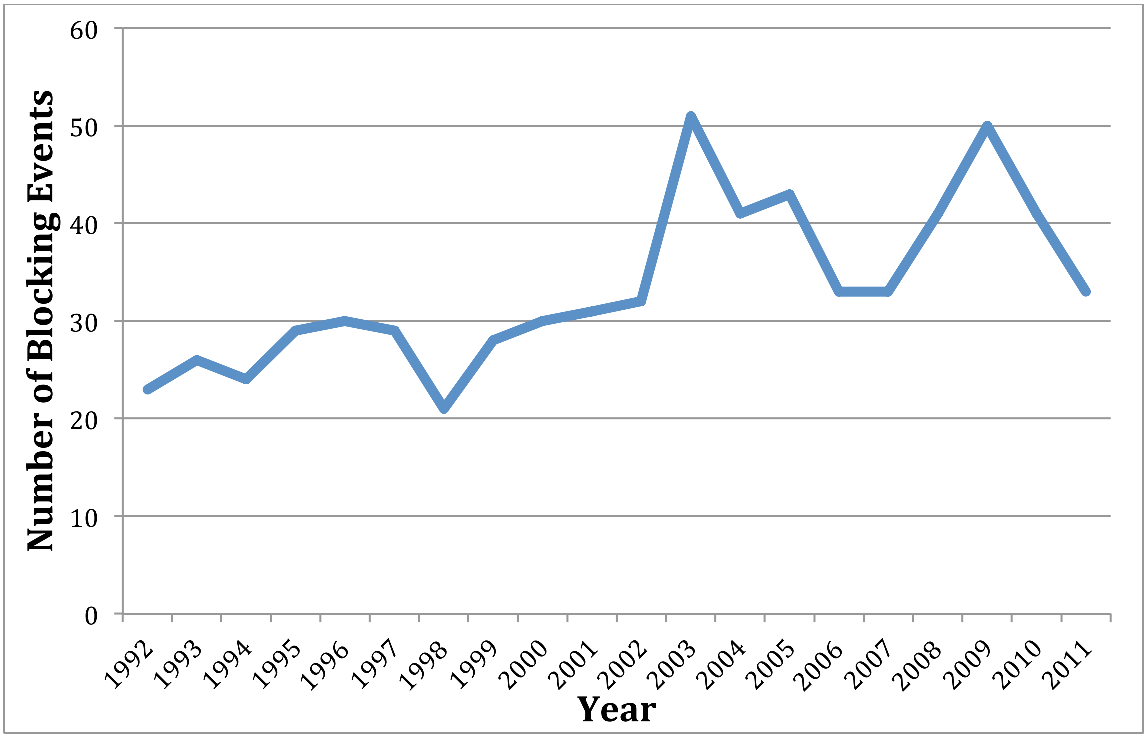

Figure 3: Number of blocking events per year.

An examination of the total number of days of which blocking occurred (Table 4) showed that in the 20-year period, 6,450 days had blocking events in the Northern Hemisphere. Therefore, of the 7,305 days between 1992 and 2011, 88.3% of the time, there was a blocking event ongoing. As anticipated, the largest number of days with blocking (1,948) was during the winter season with a well-defined maximum. The fewest blocking days were during the fall with 1,293.5 days, closely followed by the summer with 1,407 days. For geographical domains, blocking events occurred over the Atlantic, Pacific and Continental regions for 2,934, 2,051 and 1,465 days, respectively. Therefore, blocking was ongoing 40.2%, 28.1%, and 20.1% of all days over the three regions. As expected, the number of days of blocking correlated well with the seasonal and regional distribution of events. This parallels similar findings in Lupo and Smith (1995a), during their three-year blocking event study.

Table 4: Regional and seasonal distribution of the total number of blocking days.

Region	Summer	Autumn	Winter	Spring	Total
Atlantic	574	768.5	863	728.5	2934
Pacific	289.5	366.5	870.5	524.5	2051
Continental	543.5	158.5	214.5	548.5	1465
All events	1407	1293.5	1948	1801	6450 (7305 total days in sample period)

When analyzing the average duration of events (Table 5) the average length of all events in the 20-year period was 9.3 days. Atlantic region events were consistently more persistent than the others, lasting on average 10.2 days, compared to 8.5 days in the Pacific and 8.6 days in the Continental regions, respectively. In the Atlantic, there was no significant increase or decrease in duration amounts, only a slight increase during the cool seasons (10.2 and 10.5 during the autumn and winter, compared to 9.9 and 10.0 in the summer and spring). The Continental events had a noticeable boost in persistence during the spring and summer, with mean durations of 9.5 and 9.4 days, compared to the 6.3 and 7.4 days during the fall and winter.

Table 5: Regional and seasonal distribution of average duration in days of each blocking event.

Region	**Summer**	**Autumn**	**Winter**	**Spring**	**Total**
Atlantic	9.9	10.2	10.5	10.0	10.2
Pacific	8.2	8.0	8.7	8.9	8.5
Continental	9.4	6.3	7.4	9.5	8.6
All events	9.3	8.9	9.3	9.5	9.3

Comparison between mean block sizes and seasonality were similar to the average durations of events. Block sizes were on average larger in the Atlantic region during the cooler seasons of fall and winter, with a peak mean size of 2446 km during the winter (Table 6). Mean sizes were the smallest in spring and summer, with a mean block size of 2160 km and 2227 km, respectively. The peak mean winter size increased 6.5% over the mean size for all seasons. The Pacific region followed a similar trend, but peak mean block size occurred during the autumn with a gradual decrease in size toward the summer and winter seasons. However, the mean autumn block size did not increase as much as the Atlantic region, growing by 4.7% over the mean block size for the Pacific region. Despite frequent climatological and seasonal changes over land, the Continental region did not show as significant changes in mean block sizes between seasons as the Atlantic and Pacific regions. The Continental region's peak mean block size during the winter increased by just 2% over the mean size for all seasons. In general, all four seasons remained near the mean block size of 2147 km for the entire region. Analyzing all events together, the peak block sizes remained in the cooler seasons of fall and winter, with smaller sizes in the warmer months.

Table 6: Regional and seasonal distribution of average block sizes (in kilometers).

Region	Summer	Autumn	Winter	Spring	Total
Atlantic	2227	2334	2446	2160	2296
Pacific	2316	2406	2311	2193	2299
Continental	2148	2137	2153	2146	2147
All events	2217	2328	2347	2166	2262

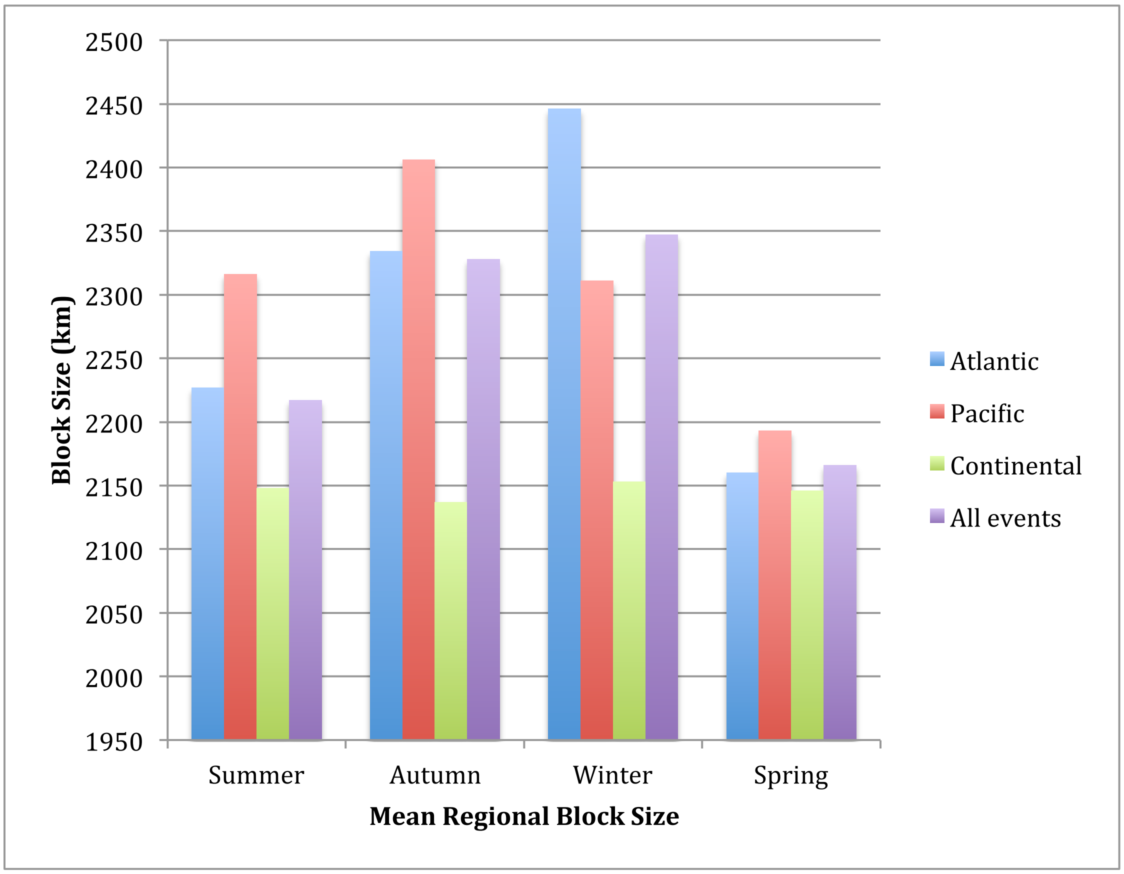

Figure 4: Regional and seasonal distribution of average block sizes.

Over the course of the 20-year study, the mean block size did gradually increase (Figure 5). In 1992, the mean block size was just over 2100 km. By 2011, the mean size was over 2700 km, nearly a 29% increase. ANOVA was performed between the two variables. The test produced an F-score of 9.71 and P-value of 0.0072. This shows the increase of mean block sizes over time to be significant above the 99% confidence level. The increase in block sizes may be linked to an increase in mean global temperatures of El Niño-Southern Oscillation, which will be discussed in Chapter 4.

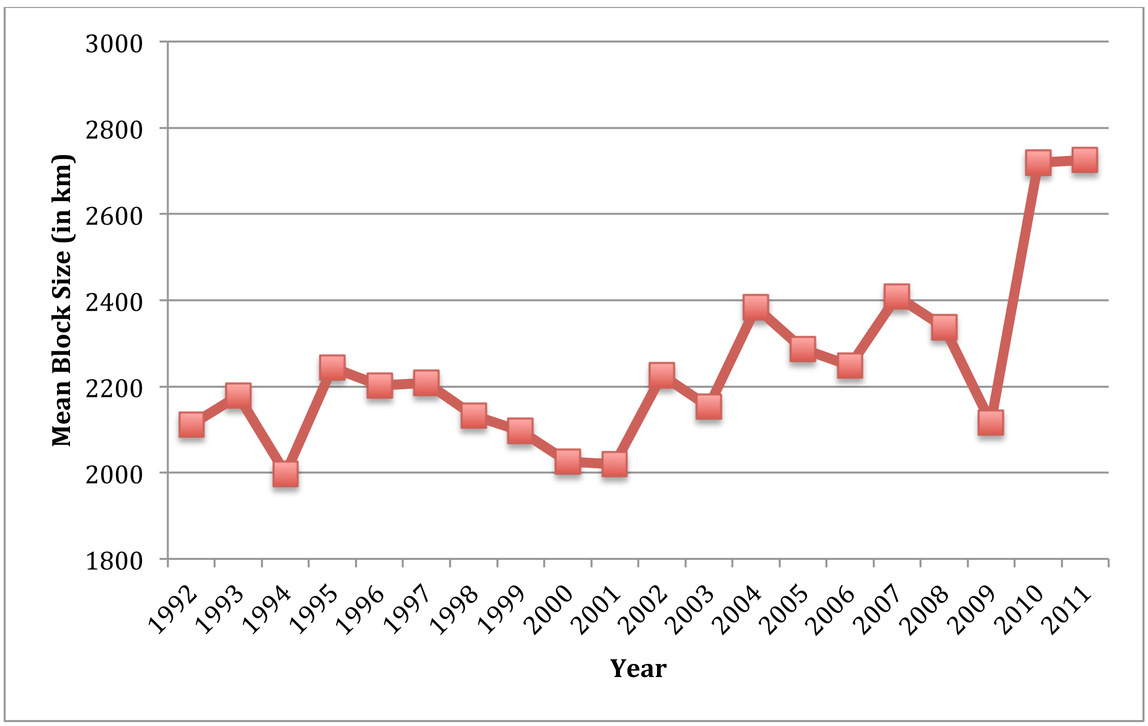

Figure 5: Annual mean block size 1992-2011.

The cause for the increase in mean size over time is not fully understood, but changes in the mean global temperatures may play a significant role. Global temperatures, over land and water, steadily increased in the 20th century, with a more pronounced climb from 1970 to present. That trend can be seen in Figure 6 from the National Oceanic and Atmospheric Administration. According to Lupo et al. (1997), a rise in global temperatures would lead to a 9.4% increase in blocking events. However, their model data showed those events in a double CO_2 simulation would have weaker blocking intensities and also be of similar or smaller size. The results from this study contradict Lupo et al. (1997)'s results and instead indicate block sizes may be increasing with a global rise in temperature. The varying size of the blocking events can be linked to interannual variability, which will be discussed further in Chapter 4.

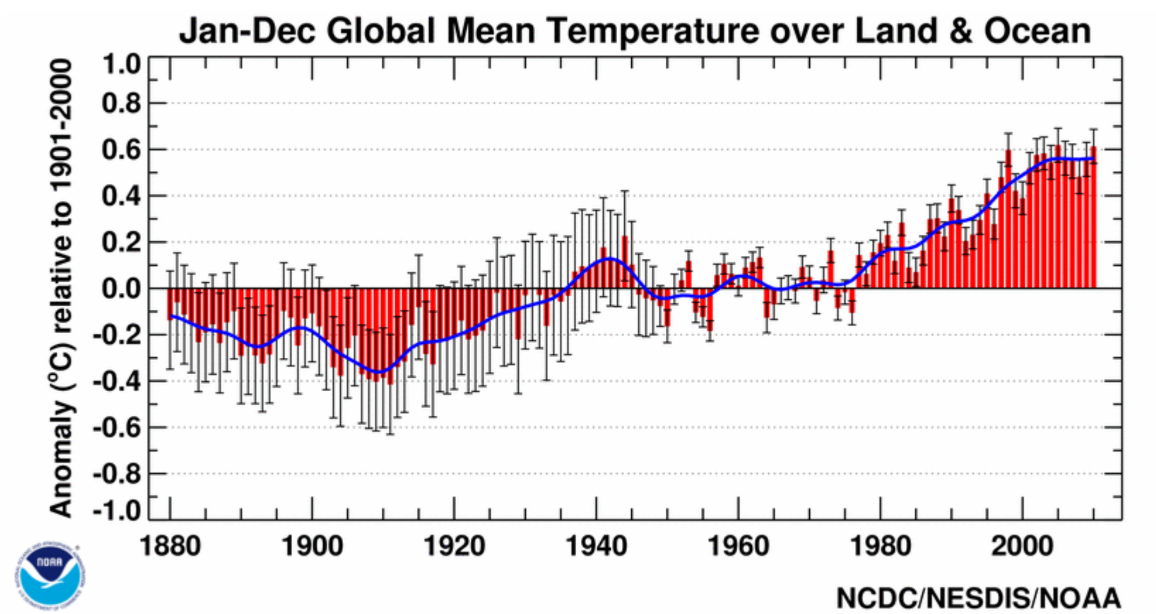

Figure 6: January-December Global Mean Temperature 1880-2010 (NOAA)
http://www.ncdc.noaa.gov/cmb-faq/anomalies.php

Individual blocking events were then compared to blocking intensity (BI), a calculated indicator for the strength of events, as defined by Weidenmann et al. (2002). The authors modified a previous index from Lupo and Smith (1995a), in order to apply the index to a much larger dataset. Lupo and Smith (1995a) calculated the BI using a normalized and scaled central height contour value to represent the flow pattern, such that BI was rated from 1 to 10, with 10 being the strongest. Weidenmann et al. (2002) modified the calculation by using a mean contour for the block area, taking into account both the upstream and downstream troughs at the same latitude as the center of the blocking event. Results from Weidenmann et al. (2002) showed that BI is proportional to the height gradient in the center of the block and therefore an indicator of the overall strength of the blocking events. The events were then categorized according to their BI value, with weak ($BI < 2.0$), moderate ($2.0 < BI < 4.3$), and strong ($BI > 4.3$).

Analyzing the intensity values compared to mean block size, the overall trend showed small block sizes were weaker, while larger blocks were stronger (Figure 7). The variables have a strong correlation between them, with an r^2 value of 0.73. A simple statistical t-test showed those results to be significant at the 99% confidence level. The block sizes were then grouped according to the Wiedenmann et al. (2002) strength categories of weak, moderate and strong. This modification led to a near-perfect, strong correlation between intensity and block size (Figure 8). The significant correlation had an r^2 value of 0.98, confirming that larger blocking sizes result in increased strength and blocked flow.

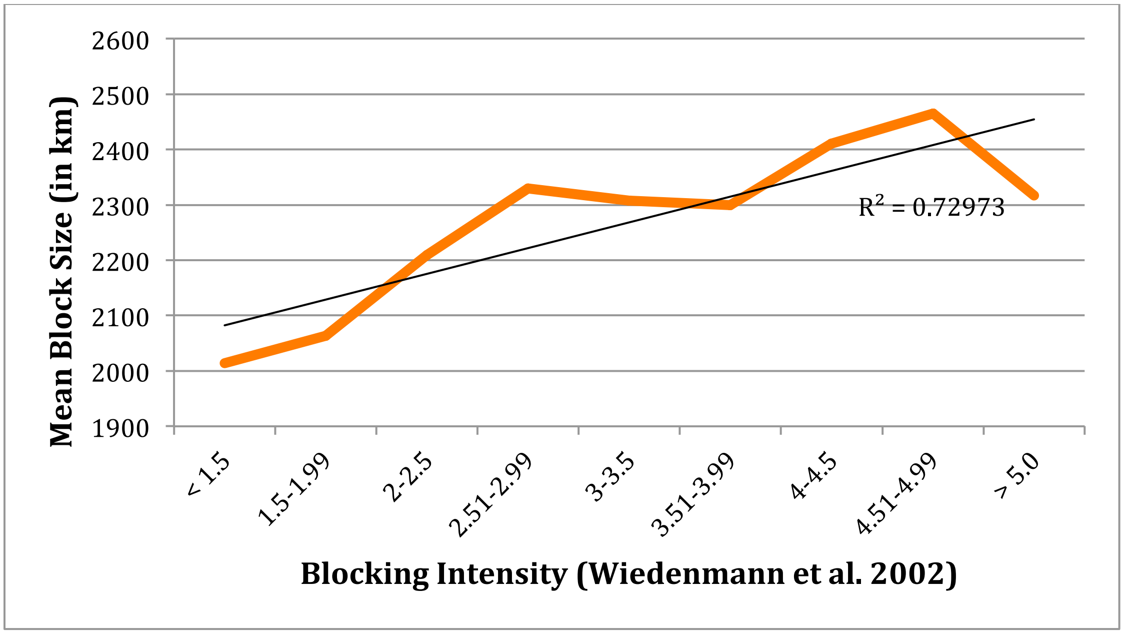

Figure 7: Mean block size compared to blocking intensity.

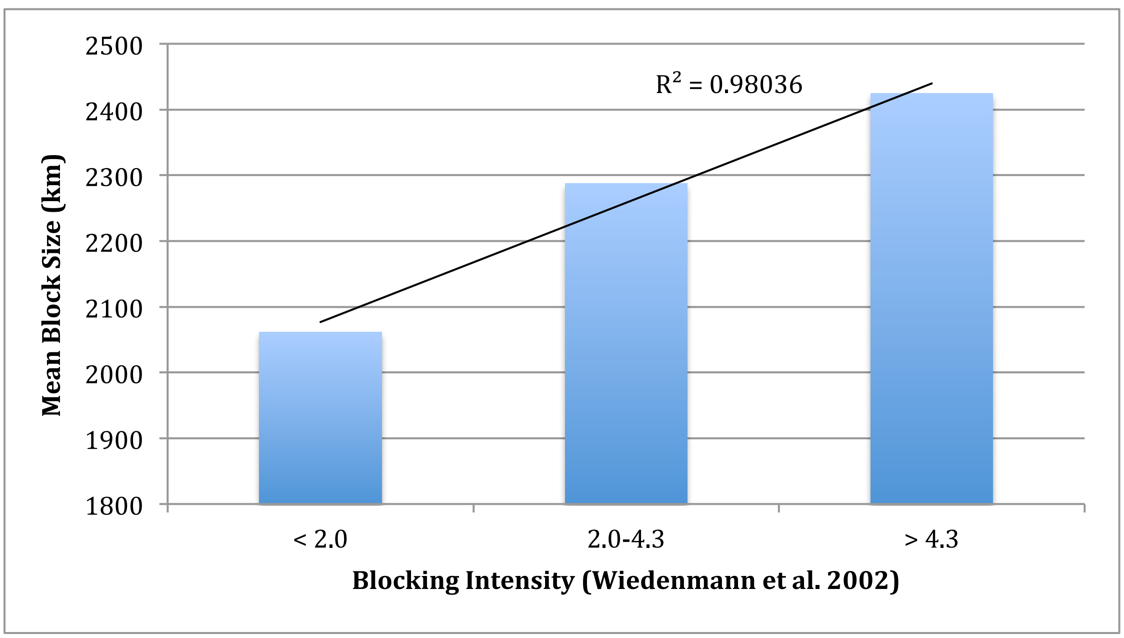

Figure 8: Mean block size compared to blocking intensity categorical groups.

3.2 ROSSBY WAVE COMPARISONS

Rossby waves are a type of planetary wave found in fluids, usually defined by large-scale atmospheric features. In general, Rossby waves, sometimes called inertia waves, owe their existence to planetary rotational motions, such as the Coriolis force, which is the restoring force. The waves are the result of cooler polar air moving southward and warmer tropical air advancing northward. The clashing air masses result in the formation of troughs and ridges, thus altering atmospheric circulation. The subsequent Rossby waves are long (short) waves, which propagate westward (eastward) and affect how the westerly winds behave. According to the American Meteorological Society and Holton (1992), wave speed is defined as:

$$c = \bar{u} - \frac{\beta}{K^2} \quad \text{(Eq. 1)}$$

Where u is the mean westerly flow, β is the Rossby parameter (expressed as the difference in the Coriolis parameter with latitude) and K is the wave number. The Rossby parameter takes into account the angular speed of Earth, mean radius and latitude. Further information and discussion on β and K can be found in Holton (1992). K^2 is equal to $\left(\frac{2\pi}{L}\right)^2$, where L is the mean wavelength. For the current work, we will analyze the wave speed of blocking events using the formula:

$$c = \bar{u} - \frac{\beta}{\left({}^{2\pi}/_{L}\right)^2} \quad \text{(Eq. 2)}$$

To calculate the wave progression of blocking events at two speeds, *u* was set at 10 m/s and 15 m/s. Blocking events have been noted to move, although slowly. The speeds of 10 and 15 m/s represent typical progressions of upper air waves. The Rossby parameter β, was made constant, with a value of 1 x 10^{-11} ms^{-1}.

When calculating the flow speed at 10 m/s, the average progression for all 669 events was 4.58 m/s. After dividing the blocks into seasonal groups (summer, autumn, winter, and spring), there was a slight variation among the seasons. The wave speeds were slowest during the cooler seasons of autumn and winter with speeds of 4.32 m/s and 4.15 m/s, respectively. They were faster during the warmer seasons of summer and spring with 4.79 m/s and 5.02 m/s. Considering the wave speed equation (Eq. 2) accounts for the mean wavelength of blocks, the speed correlates with the size of blocks. Larger block sizes during the warmer months appear to move more compared to the smaller blocks during the fall and winter.

When calculating the flow speed at 15 m/s, the average progression for all of the blocking events increased to 9.58 m/s. The same characteristics were seen when breaking the blocks into seasons. Events in the cooler seasons progressed slower with speeds of 9.32 m/s and 9.15 m/s during autumn and winter. Blocks progressed faster during the spring and summer with speeds of 10.02 m/s and 9.79 m/s, respectively. Again, since the wave speed equation factors in blocking sizes, it is fitting that larger blocks in the warmer months would progress quicker than smaller blocks in the cooler seasons.

Calculations were then completed to find the sizes of theoretical blocks with the flow speeds of 10 m/s and 15 m/s. Setting *c*, the wave speed, to zero (c = 0) and solving for the mean wavelength L, a hypothetical blocking event would be 3141.6 km given a flow speed of 10 m/s. The size increases to 3847.6 km for a stationary block with a flow speed of 15 m/s. Though the block sizes are much larger than the mean 2262 km block size for all of the events in this study, 32 of the 669 blocks were larger than 3141 km. Therefore it is plausible for blocks to progress at speeds of 10 to 15 m/s, depending on the strength of westerly winds.

Using the mean wave speed progressions for the events, calculations were completed to find out how far blocking events could move over the course of their lifetime. If a block were to have a wave speed of 4.58 m/s, it could progress 395.7 km/day or approximately 3.6° latitude. Increasing the wave speed to 9.58 m/s, the block would progress 827.7 km/day or 7.5° latitude. Considering the average block size for the 20-year study is 2262 km, a block could move 17% to 37% of its mean size each day, depending on the speed of the westerly winds.

The movement of blocking events, however, is subjective. The criteria for identifying blocks varies among publications and their definitions include specifications on minimal longitudinal and latitudinal boundaries as well as locations. While these blocking movements could change depending on the definition, they do confirm that over the duration of a block's lifetime, there is some motion depending on planetary motions and the westerly flow.

EL NIÑO-SOUTHERN OSCILLATION

Characteristics of blocking events during El Niño-Southern Oscillation were previously discussed in Chapter 1.3. As stated earlier, numerous studies (Renwick and Wallace 1996, Mokhov and Tikhonova 2000, Watson and Colucci 2002, Wiedenmann et al. 2002, and Barriopedro et al. 2006) focused on relationships between interannual variability and blocking. It was shown that blocking events are stronger and more persistent during La Niña, with an increase in the number of blocking days but not duration (Weidenmann et al. 2002). Mokhov and Tikhonova 2000 showed blocking increased during La Niña and neutral years over Continental regions. In El Niño years, Renwick and Wallace (1996) found that blocking was suppressed when compared to neutral years and La Niña.

During El Niño and La Niña years in this research, the mean number of events increased, correlating well with previous studies that showed a higher frequency during EN and LN. For all regions, the average number of events in EN and LN were 35.8 and 36.3 respectively, up from 32.6 for neutral years. The most prominent increases over neutral years were seen in the Atlantic and Continental regions, while in the Pacific, the gain was much smaller.

Table 7: The mean Northern Hemisphere blocking characteristics by region, including events, total blocking days, duration and block sizes (EN/NEU/LN).

Region	Events	Days	Duration	Size
Atlantic	15.4/13.6/14.7	149.5/154.3/136.2	9.6/10.5/9.3	2407.5/2324.7/2103.5
Pacific	10.8/10.7/11.0	97.6/89.7/95.3	8.8/8.3/8.9	2397.1/2290.5/2089.5
Continental	9.6/7.5/10.7	80.2/69.0/85.8	8.1/8.5/8.1	2188.8/2084.9/2009.2
Total	35.8/32.6/36.3	327.3/313.0/316.0	8.9/9.4/8.7	2339.2/2261.3/2077.7

The results of blocking days closely resembled results from Wiedenmann et al. (2002). Overall, the number of blocking days increased for the entire hemisphere during EN and LN years, however, in the Atlantic, blocking days decreased by 11.7%. Only in the Pacific and Continental regions did the number of days increase, with substantial gains over land. Over Continental regions, blocking days increased by nearly 25% during LN years, a result similar to Mokhov and Tikhonova (2000). Unlike their results, more blocking did not occur during neutral years over Continental regions in this 20-year period.

Analyzing the duration of events, the overall trend was for all Northern Hemisphere blocking events to be less persistent. During neutral years, the average duration was 9.4 days. That duration decreased to 8.9 and 8.7 days for EN and LN years for the entire hemisphere. While events were less persistent for the entire hemisphere during EN and LN years, especially in the Atlantic and Continental regions, the events were more persistent in the Pacific. A similar finding in Wiedenmann et al. (2002) showed that Pacific blocking events were more persistent during ENSO years.

Across the Northern Hemisphere, mean block sizes increased during El Niño years when compared to neutral years. Plotting ENSO years against mean block sizes (Figure 9), small peaks are visible during EN years, most noticeably in 1997 and 2006. Decreasing block sizes for LN years are also shown, although there is no clear or distinct year-to-year graphical trend for overall block sizes. For the hemisphere, blocking sizes increased from 2261.3 km during neutral years to

2339.2 km during EN. Similar increases were seen in all three regions of block formation. During LN years, blocking sizes were suppressed for the entire hemisphere and for all three regions. The mean size for the hemisphere decreased 8.1% to 2077.7 km. Although the decrease in size was minor over the Continental region, blocks were on average 9.5% and 8.8% smaller in the Atlantic and Pacific regions, respectively.

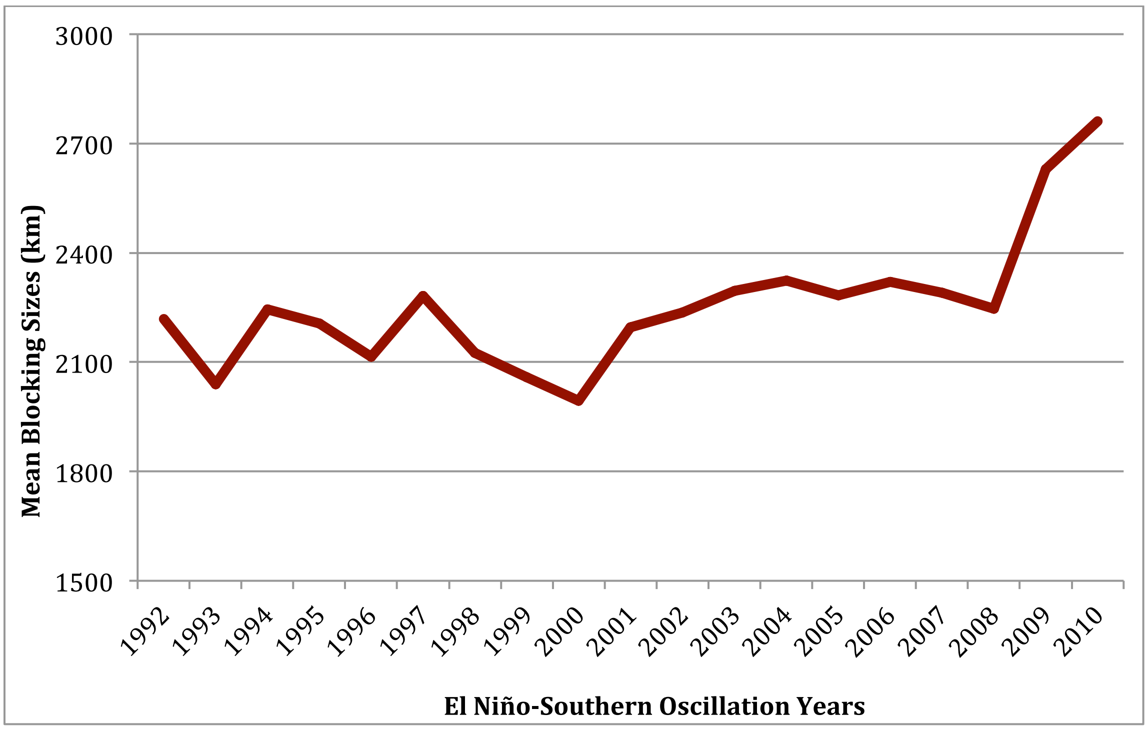

Figure 9: Mean block size during El Niño-Southern Oscillation years.

Table 3 (Reprinted): A list of years in this study divided into El Niño-Southern Oscillation phases.

El Niño (EN)	Neutral (NEU)	La Niña (LN)
1997 2002 2006 2009	1992-1996 2000 2001 2003-2005 2008	1998 1999 2007 2010

A Fourier transform was then completed on the mean ENSO year blocking sizes. The transform showed peaks at approximately 2.5 and 1.67 cycles per decade (Figure 10). This would result in cycles of four to six years, which correlates well with the typical ENSO cycle of three to seven years. The transform shows that block sizes, when connected to ENSO years, follow a cyclical trend depending on which phase of ENSO is present. The Fourier transform also demonstrated a 95% statistical significance with the cycles. Therefore, the variation in mean blocking sizes during El Niño, La Niña and neutral years can be linked to cycles in the ENSO.

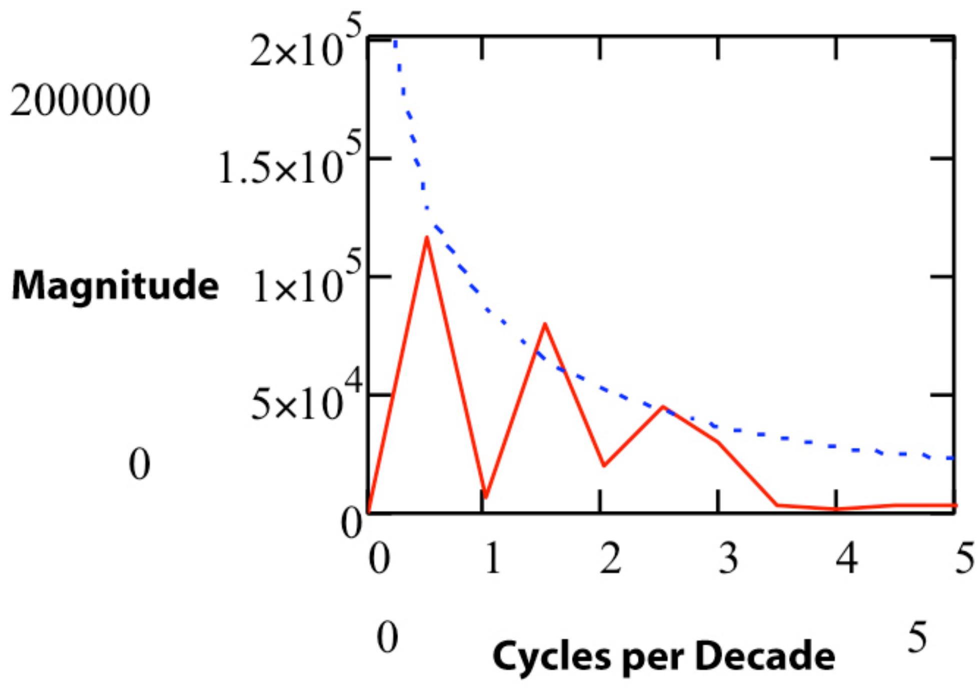

Figure 10: Fourier transform of El Niño-Southern Oscillation cycles.

DISCUSSION & CONCLUSION

5.1 DISCUSSION

This study took the most recent 20-year sample of 669 blocking events and analyzed their sizes and seasonal and interranual variability. Events were retrieved from the University of Missouri-Columbia blocking database and defined as blocking events using the definition of Lupo and Smith (1995). Then using gridded reanalyses data from the National Center for Environmental Prediction and the National Center for Atmospheric Research, the mean size was calculated for each event using a simple Rossby wave equation.

Blocking events averaged 33 blocks per year, a substantial increase of the 21 to 27 events found in previous studies (Triedl et al. 1981, Lejenas and Okland 1983, Lupo and Smith 1995a, Wiedenmann et al. 2002 and Barriopedro et al. 2006). The growing number of blocking events, which was shown to be statistically significant above the 95% confidence level, coincides with global mean temperature over land and water increasing, according to the National Oceanic and Atmospheric Administration. This finding supports earlier research that predicted the annual number of blocks would increase with a rising global temperature. Notably, Lupo et al. (1997) concluded a warmer world with double CO_2 would result in weaker and smaller blocks, which this research contradicts. Blocking sizes have increased through the years in this study. Between 1992 and 2011, block sizes increased by 29%. That increase was shown to be statistically significant at the 99% confidence level. Analyzing the seasonality of block sizes concluded that overall, blocks were larger during winter. In the Atlantic, peak size was in winter, while in the Pacific, the largest blocks occurred in autumn. Those peaks were 6.5% and 4.7% greater than the mean block size for their respective region. In the Continental areas, there was no substantial increase in any given season, although blocks were slightly larger during autumn and winter.

Blocking sizes were also directly connected to blocking intensity. The strength index, modified by Wiedenmann et al. (2002), assigns each blocking event a value based on height contours of the block in order to represent the flow pattern. The comparison between the sizes of blocks and blocking intensity was shown to have a high correlation. As expected, larger blocks are stronger (i.e. block flow) relative to smaller blocks.

The movement of blocking events was analyzed using a modified Rossby wave equation. Calculating the motion of blocks at two different speeds showed that blocks move on average 4.58 m/s with a flow speed of 10 m/s, and at 9.58 m/s when the flow speed is 15 m/s. Dividing the events seasonally revealed that blocks moved slower during the cooler seasons of autumn and winter and faster during summer and spring. Since the Rossby wave equation accounts for the size of blocks, events that are larger in the summer and have a larger wavelength progress faster than smaller events in the autumn and winter. The study also calculated the theoretical sizes of blocks to move consistently with flow speeds of 10 m/s and 15 m/s. Results showed a block would need to be 3141.6 km to move at 10 m/s and 3847.6 km to move at 15 m/s. Although those sizes are considerably larger than the mean block size for this 20-year study, nearly 4.8% of the 669 blocks are larger than 3141 km, so it is plausible for a block to progress at those wave speeds. Depending on the speed of the westerly winds, blocking events can move significant distances during the course of their lifetime. It was shown that a block with that wave speed of 4.58 m/s could travel 395.7 km/day or nearly 3.6° latitude. A wave speed of 9.58 m/s would allow the block to move 827.7 km or 7.5° latitude per day. Therefore, the average block event in this study could move 17% to 37% of its mean size every day, depending on the westerly winds.

Blocking events were analyzed in relation to El Niño-Southern Oscillation phases. In all regions, the number of events increased during El Niño (358) and La Niña (363) years compared to those in neutral (326) years. The number of blocking days increased overall for EN and LN years, which parallels findings from Weidenmann et al. (2002) who found increased blocking days during LN, but there were differences depending on block location. Blocking days decreased over the Atlantic in EN and LN compared to neutral years, but increased substantially during LN over the Continental regions, a similar result to Mokhov and Tikhonova (2000). However, this study showed fewer blocking events occurred over Continental regions during neutral years, which contradicts their findings. Results also showed differences in block sizes during the different ENSO phases. For the entire hemisphere, block sizes increased approximately 3% during EN compared to neutral years. The opposite occurred during LN years, when block sizes decreased. Sizes decreased over 8% for the entire hemisphere, with more prominent decreases of 9.5% and 8.8% in the Atlantic and Pacific regions, respectively. A Fourier transform of ENSO block sizes showed with a 95% statistical significance that block sizes are linked to interannual variability. The Fourier transform revealed peaks at 1.67 and 2.5 cycles per decade, which correlates strongly with ENSO phase cycles of four to six years.

5.2 CONCLUSION

This study confirmed previous findings and revealed new results about blocks in the Northern Hemisphere. Among the new findings:

- The number of blocking events occurring per year is increasing with a trend that was shown to be significant exceeding the 95% confidence level.
- Block sizes have been growing between 1992 and 2011, with a statistical correlation at the 99% confidence level.
- Connections between mean block size and block intensity as well as variations in block sizes and ENSO phases showed high correlation.
- Blocks were also shown to move substantially using the simplified Rossby wave equation. Although the definition of blocking events varies, the results from this work confirm that blocks are not stationary, permanent atmospheric features, but can move depending on planetary motions and westerly winds.

Though atmospheric blocking may not be as widely known as other meteorological phenomena, its effects can be just as far-reaching. Recently, blocking has led to significant heat waves, droughts, and even flooding (Lupo et al. 2011). The mechanistic onset and termination of blocking events is not well understood and long-range forecasters lack the ability to accurately predict when a blocking event will form, let alone its duration, strength or exact location. Within recent decades though, researchers been able to identify formation regions and blocking's connection to storm tracks. The findings of this research, along with a growing number of studies analyzing the climatology and dynamics of atmospheric blocking, will hopefully help to further knowledge about blocking and help forecasters better understand and predict events.

REFERENCES

Barriopedro, D., R. García-Herrera, A. R. Lupo, and E. Hernández, 2006: A climatology of Northern Hemisphere blocking. *J. Climate*, **19**, 1042–1063.

Birk, K.A., A.R. Lupo, P.E. Guinan, and C.E. Barbieri, 2010: The interannual variability of Midwestern temperatures and precipitation as related to the ENSO and PDO. *Atmofera,* **23**, 95-128.

Dole, R. M. and Gordon, N. D. 1983. Persistent anomalies of the extratropical Northern Hemisphere wintertime circulation: Geographical distribution and regional persistence characteristics. *Mon. Wea. Rev. III*, 1567-1586.

Fournier, A., 2000: Introduction to orthonormal wavelet analysis with shift invariance: Application to observed atmospheric blocking spatial structure. *J. Atmos. Sci.*, **57**, 3856–3880.

Holton, J. R., 1992: *An Introduction to Dynamic Meteorology*, 3d edition, Academic Press, 216–222.

Key, J. R., and A. C. K. Chan, 1999: Multidecadal global and regional trends in 1000 mb and 500 mb cyclone frequencies. *Geophys. Res. Lett.*, **26**, 2053-2056.

Lejenäs, H. and økland, H., 1983: Characteristics of northern hemisphere blocking as determined from a long time series of observational data. Tellus A, **35A**: 350–362.

Lupo, A.R., I.I. Mokhov, M.G. Akperov, A.V. Cherokulsky, H. Athar, 2011: A dynamic analysis of the role of the planetary and synoptic scale in the summer of 2010 blocking episodes over the European part of Russia. *Submitted to Adv. in Metrology.*

Lupo, A.R., and P. J. Smith, 1995: Climatological features of blocking anticyclones in the Northern Hemisphere. *Tellus*, **47A**, 439–456.

Lupo, A.R. and P.J. Smith, 1998: The interactions between a midlatitude blocking anticyclone and a synoptic-scale cyclone occurring during the summer season. *Mon. Wea. Rev.*, **126**, 503–515.

Lupo, A.R., R.J. Oglesby and I.I. Mokhov, 1997: Climatological features of blocking anticyclones: a study of Northern Hemisphere CCM1 model blocking events in present-day and double CO_2 concentrations. *Clim. Dyn.*, **13**, 181-195.

Mokhov, I.I., and E. A. Tikhonova, 2000: Atmospheric blocking characteristics in the Northern Hemisphere: Diagnostics of changes. Research Activities in Atmospheric and Ocean Modeling, WMO/TD-987, 1 p.

Quiroz, R. S. 1987. Traveling Waves and Regional Transitions in Blocking Activity in the Northern Hemisphere. *Mon. Wea. Rev.* **115**, 919–935.

Renwick, J. A., and J. M. Wallace, 1996b: Relationships between North Pacific wintertime blocking, El niño, and the PNA pattern. *Mon. Wea. Rev*, **124,** 2071–2076.

Rex, D. F., 1950a: Blocking action in the middle troposphere and its effect on regional climate I: An aerological study of blocking action. *Tellus*, **3**, 196–211.

Rex, D.F., 1950b: Blocking action in the middle troposphere and its effect on regional climate II: The climatology of blocking action. *Tellus*, **3**, 275–301.

Shabbar, A., J. Huang, and K. Higuchi, 2001: The relationship between the wintertime North Atlantic Oscillation and blocking episodes in the North Atlantic. *Int. J. Climatol.*, **21**, 355–369.

Triedl, R.A., Birch, E.C., and Sajechi, P. 1981. Blocking action in the Northern Hemisphere. A climatological study. *Atmos.-Ocean* **19**, 1-23.

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

Tyrlis, E., and B. J. Hoskins, 2008a: Aspects of a Northern Hemisphere atmospheric blocking climatology. *J. Atmos. Sci.*, **65**, 1638–1652.

Watson, J. S., and S. J. Colucci, 2002: Evaluation of ensemble predictions of blocking in the NCEP global spectral model. *Mon. Wea. Rev.*, **130,**3008–3021.

Whittaker, L. M., and L. H. Horn (1982), *Atlas of Northern Hemisphere Extratropical Cyclone Activity, 1958–1977*, Dept. Meteorol., Univ. Wisconsin, Madison, Wis.

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