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Changes in Blocking Characteristics During the First Part of the 21st Century.

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Abstract: A global blocking climatology published by this group for events that occurred during the late 20th century examined the comprehensive list of characteristics that included block intensity. In addition to confirming the results of other published climatologies, they found that Northern Hemisphere blocking was stronger than Southern Hemisphere events and winter events are stronger than summer ones. This work also examined the interannual variability of blocking as related to El Nino. Since this time, there is evidence that the occurrence of blocking has increased globally. A comparison of blocking characteristics during the first part of the 21st century to those in the late 20th century shows that the number of blocking events and their duration have increased in the Northern and Southern Hemisphere. The intensity of blocking has decreased by about nine percent in the Northern Hemisphere, but there was little change in the intensity of Southern Hemisphere events. Additionally, there is little or no change in the genesis regions of blocking. An examination of variability related to El Nino and Southern Oscillation reveals that the variability found in the earlier work has reversed. This could either be the result of interdecadal variability or a change in the climate.

Keywords: blocking; ENSO; climate change; Pacific Decadal Oscillation;

1. Introduction

Many recent studies have examined the climatological behavior of blocking in both the northern and Southern Hemispheres in the later part of the 20th century [1-7]. Only a few have examined blocking in the 21st century (e.g. [8], [9]). Many have also examined projections for the future occurrence of blocking [7], [10-13]. Also, there is some evidence to suggest that there has been an increase in the occurrence of blocking since 2000 in both the northern and Southern Hemispheres.

The study of [1] and [7] studies examine a long list of blocking chracteristic including the number of events, days, duration, intensity, and location at onset. Most other climatologies use only the occurrence, day, and/or durations of blocking events. The work of [5] suggested interannaul and interdecadal variability in block occurrences. Then [6] implies that the number of Northern Hemisphere blocking events is increasing, but that the period 1970-1999 was likely a period of low blocking occurrence. Many authors projected that the occurrence of blocking many increase in a warmer world [7], [10], [12], [13]. Others projected that far into the future the number of events may decrease slightly [11]. Others, such as [8] and [9] suggest that the primary location for block ccurrences would also change in a warmer world.

The goal of this work is to make a comprehensive comparison of the global occurrence of blocking since the end of the climatology of [1] to their work for the late 20th century. This work will examine the more comprehensive characteristics that they researched. This study will also determine if there has been any changes in the trends or interannual variability of any of these variables, as well as the possibility of interdecadal variability in these variables. This study is unique in that it is the only study that includes an examination of block intensity (BI). BI has been shown to be related to the 500 hPa height gradients in each hemisphere [1]. This work will primarily use the National Centers of Environmental Prediction / National Center for Atmospheric Research (NCEP / NCAR) reanalyses.

2. Data and Methods

2.1 Data

The data used here were the NCEP / NCAR reanalyses 500 hPa height fields on a 2.5^{o} latitude by 2.5^{o} longitude gridded data set available at 6-h intervals [14], [15]. The 1200 UTC data was used primarily in the calculation of intensity since these tended to have the most number of observation data. This study also used data archived at [16] which contains a list of all blocking events since the beginning of the [1] study. The period of study in the Northern Hemisphere is from July 1998 to June 2017 (19 additional seasons), while for the Southern Hemisphere included the period from January 2000 to December 2016 (17 additional seasons). These time periods (spatial regions) follow the blocking year (geographic regions) established by [1].

2.2. Methodology

The blocking criterion and block intensity used here were established by [1] and references therein. The definition for ENSO used here is described in [17] and references therein and a short description is given here. The Japanese Meteorological Agency (JMA) El Nino and Souther Oscillation (ENSO) index is available through the Center for Ocean and Atmospheric Prediction Studies (COAPS) from 1868 to present [18]. The JMA classifies ENSO phases using SST within the bounded region of 4˚S to 4˚N, 150˚W to 90˚W, and defines the inception of an ENSO year as 1 October, and its conclusion on 30 September of the next year. This index is widely used in other published works (see [17] and references therein) and a list of years is given in (Table 1). Also, [19] found that while the JMA index is more sensitive to La Niña events than other definitions, it is less sensitive than other indices to El Niño events.

Table 1. List of ENSO years used here. The years are taken from [18].

El Niño	Neutral	La Niña
1969	1968	1967
1972	1977-1981	1970-1971
1976	1983-1985	1973-1975
1982	1989-1990	1988
1986-1987	1992-1996	1998-1999
1991	2000-2001	2007
1997	2003-2005	2010
2002	2008	
2006	2011-2013	
2009	2016-2017	
2014-2015		

The Pacific Decadal Oscillation (PDO) positive and negative modes are catalogued also by the Center for Ocean-Atmospheric Prediction Studies (COAPS). The most important effect of PDO is how it interacts with ENSO during certain phases to create an enhanced effect on temperatures and precipitation variability (e.g. [20], [21]). The characteristics of these modes are less pronounced than those for ENSO due to the fifty-to seventy-year cycle of PDO [22], [23]. The positive phase of the PDO is recognized as the period 1977-1998, and the negative phase is recognized as the years 1947 – 1976, and 1999 – 2017.

3. The Climatology of Blocking in the Early 21st Century

3.1 The Northern Hemisphere.

The noteworthy character of blocking at the start of the 21st century (Table 2) is the increases in the occurrence, number of blocking days and durations. In all regions and seasons, these increases are statistically significant at the 95% confidence level, using the Z-score test for means [24]. The Atlantic region showed the weakest increases which is consistent with the results of [7]. The large increase in the occurrence and days within Pacific Region Blocking is consistent with the results of [17] who examined spring and summer blocking in this region. The work of [25] also showed a large increase in blocking for the eastern Europe and western Russia region for the spring and summer seasons as well. Only the block intensity (BI) showed a decrease over the first part of the 21st century. This decrease is not significant at any standard level of statistical significance.

Table 2. Character of Northern Hemisphere blocking events per year as a function of region and season for all characteristics since the study of [1]. The change in the value is expressed as a percentage.

Region	Occurrence	Duration	Days	Intensity
Atlantic (ATL)	**16.0 / +25.0***	10.5 / +11.7	**167.4/+54.7***	**3.20 / -7.5***
Pacific (PAC)	**11.9 / +80.3***	**9.5 / +25.0***	**112.9/+124.5***	3.19 / -1.0
Continental (CON)	**10.2 / +85.5***	9.0 / +11.1	**91.2/+105.4***	**2.49 / -5.7***
Total	**38.1 / +58.1***	9.5 / +11.8	**360.4/+70.6***	**3.03 / -5.9***
Season	**Occurrence**	**Duration**	**Days**	**Intensity**
Summer (Su)	**8.1 / +55.8***	**10.1 / +31.2***	**81.2 / +103.0***	2.32 / +4.5
Fall (F)	**8.5 / +57.4***	**9.6 / +18.5**	**81.9 / +85.7***	**3.43 / -6.5***
Winter (W)	**10.2 / +43.7***	9.7 / +9.0	**98.6 / +63.5***	**3.71 / -7.3***
Spring (Sp)	**11.4 / +56.2***	**9.7 / +22.8***	**110.2 / +91.3***	2.65 / -2.9

Such increases across all regions and seasons were suprising, however, as shown above, several studies have examined blocking over limted regions and seasons and shown similar strong inceases. While [17] and [25] showed increases within the warm season in recent decades, on the other hand, [6] showed that over the Atlantic for the winter season that blocking days over the same period covered by [1] was associated with a significant minimum. Additionally, [7] showed an increase in blocking since 2000 as shown with three blocking indexes including the index used here. Taken together, these provide confidence that the increases in Northern Hemisphere blocking occurrence is likely real. Finally, the mean number of simultaneous blocking days (defined as the number of days with two or more blocking events occurring concurrently in any sectors) per year since [1] is 103.8 days or 28.4% of the year. This represents a large increase over [1] who found the number to be approximately 8.7% of the year.

3.2 The Southern Hemisphere

Examining blocking in the Southern Hemisphere (Table 3) and comparing with the work of [1] shows similar results to the Northern Hemisphere above. The weakest increases occurred within the Pacific Region, and unlike the Northern Hemisphere this region is the predominant blocking region accounting for about three-quarters of all events when counting events and blocking days. The Pacific Region incereases in the Southern Hemisphere were weaker than their Northern Hemisphere counterparts, but still statistically significant at the 95% confdence level. Increases within the Atlantic or Indian Ocean Regions were very large, however, blocking in this region is not as prominent. Only BI showed no significant change in the Southern Hemisphere. Lastly, the number of simultaneous blocking days ber year since [1] in the Southern Hemisphere is 15.5 days per year (4.3%) which is higher than the 1.5% found by [1] and this will be discussed more below.

Table 3. Character of Southerrn Hemisphere blocking events per year as a function of region and season for all characteristics since the study of [1]. The change in the value is expressed as a percentage.

Region	Occurrence	Duration	Days	Intensity
Atlantic (ATL)	**1.7 / +88.9***	6.6 / +9.9	**10.9/+96.0***	**2.68 / -13.0***
Pacific (PAC)	**11.7 / +48.1***	**8.4 / +12.8***	**98.0/+67.0***	**2.89 / +8.2***
Indian (IND)	**2.6 / +188.9***	7.2 /-4.3	**18.4/+170.6***	**2.63 / -5.7**
Total	**15.9 / +63..9***	**8.0 / +9.0***	**126.7/+78.2***	2.84 / +0.7
Season	**Occurrence**	**Duration**	**Days**	**Intensity**
Summer (Su)	**1.9 / +58.3***	6.8 / +7.7	**13.3 / +70.5***	**2.88 /+7.7***
Fall (F)	**5.1 / +60.0***	**8.1 / +7.5**	**42.0 / +60.3***	3.02 / +2.4
Winter (W)	**5.4 / +68.8***	**8.3 / +9.3***	**45.3 / +84.1***	2.91 / +2.5
Spring (Sp)	**3.2 / +77.8***	**7.8 / +14.7***	**26.0 / +111.4***	**2.41 / -8.4***

4. Interannual and Interdecadal variability

In this section, the change in ENSO variability as well as PDO variability will be examined. In order to accomplish the latter, the data from [1] will be reanalyzed by stratifying the blocking years using the PDO epochs defined in Section 2.2. The change in phase of the PDO occurred near the end of the [1] study, thus it might be reasonable to assume that the recent increases in blocking are related to the change in pahse of the PDO. The results from the Northern Hemisphere are shown in Table 4. The results show that the total number of blocking events, days, and durations were higher for the –PDO, but the BI indicated weaker events similar to the occurrence of blocking after the [1] study. Addtionally, during the +PDO, the ENSO variability matched that of [1] which implied that La Nina years were associated with more blocking events and days and which were slightly stronger. Then during the –PDO phase the ENSO variability was the opposite in that El Nino years were associated with the greater number of blocking events, days, and slightly stronger. Thus, by examining the overall set of years (49) there was little ENSO variability overall.

In the Southern Hemisphere (Table 5), as in the Northern Hemisphere, the occurrence of blocking was greater during the –PDO phase. In this part of the world, however, the ENSO variability did not change across the phase of the PDO. During both PDO epochs, blocking occurred more often, was more persistent and more intense in El Nino and Neutral years as compared to La Nina years. This variability is reflected across each region as well. The study of [1] speculated that blocking was on the decrease during the late 20th century. Lastly, [26] showed that there was a reversal in the proportion of east Pacific blocking occurrences when compared to those of the west Pacific Region.

During the +PDO phase there were a larger fraction of east Pacific Region blocking during La Nina and Neutral years, while the opposite was true during the –PDO epoch (La Nina years showed the smallest fraction of east Pacific blocking).

Table 4. Character of Northern Hemisphere blocking events per year as a function of ENSO and PDO. The number of years in each category is shown in parenthesis.

+ PDO	Occurrence	Duration	Days	Intensity	% Simult.
El Nino (6)	23.5	8.1	190.4	3.06	7.6
Neutal (15)	24.4	8.2	200.1	3.26	8.9
La Nina (2)	30.5	8.3	253.3	3.11	12.7
Total (23)	24.7	8.2	202.5	3.20	8.9
- PDO	**Occurrence**	**Duration**	**Days**	**Intensity**	**% Simult.**
El Nino (7)	37.0	9.6	355.2	3.13	24.4
Neutral (12)	37.4	9.9	369.7	3.05	28.2
La Nina (8)	29.1	8.4	244.4	3.08	13.9
Total (27)	33.4	9.9	329.0	3.08	22.5

Table 5. Character of Southern Hemisphere blocking events per year as a function of ENSO and PDO. The number of years in each category is shown in parenthesis.

+ PDO	Occurrence	Duration	Days	Intensity	% Simult.
El Nino (5)	9.0	7.0	63.2	3.02	1.7
Neutal (15)	9.5	7.1	67.3	2.76	1.4
La Nina (2)	6.0	6.7	40.3	2.74	0.0
Total (22)	9.0	7.1	63.9	2.83	1.3
- PDO	**Occurrence**	**Duration**	**Days**	**Intensity**	**% Simult.**
El Nino (8)	14.8	8.4	124.6	2.96	3.9
Neutral (10)	16.5	7.8	128.8	2.78	4.1
La Nina (8)	12.0	7.6	90.6	2.73	2.7
Total (26)	14.6	7.9	115.8	2.83	3.6

The work of [1] speculated that the greater occurrence of simultaneous blocking events in the Northern Hemisphere versus those in the Southern Hemisphere was due to the greater number of occurrence of blocking since previous work demonstratd that the occurrence of blocking was caused local synoptic processes rather than hemisphere-wide planetary-scale processes. The results here show a similar result since the fewest number of blocking events occurred during the Southern Hemisphere +PDO epoch as well as the fewest number of simultaneous days. The opposite was true in that the largest number of simultanoues blocking days occurred during the Northern Hemisphere –PDO epoch which showed the largest number of blocking occurrences. The correlation between the number of simultaneous blocking days and the number of events was 0.89 in the Northern Hemisphere and 0.74 for the Southern Hemisphere and both results are statistically significant at the 99% cofindence level.

5. Discussion, Summary, and Conclusions

This study examined the occurrence of blocking over the entire globe since the study of [1], and including such characteristics as occurrence, duration, blocking days, block intensity (BI), and the number of simultaneous blocking days. The data set used here was the NCEP/NCAR re-analyses and the archive of blocking events are found at [16]. Then, the long term trends as well as interannual and interdecadal variability were examined.

The study here showed statistically significant increases in block occurrences, days, and duration since the end of the 20th century. In the Northern Hemisphere there was a slight decrease in BI, which was not statistically significant. There was little change in the Southern Hemisphere BI. In the Northern Hemisphere, the increses found here were consistent with the results of others [6], [7], [17], [25] who examined 'partial' climatologies examining only certain reigions during certain seasons. The work of [6] implied that the period 1970 – 1999 showed a relative minimum in Atlatnic Region winter season blocking. Thus, there is strong evidence to support the results here. In the Southern Hemisphere, Pacific Region blocking showed increases that were not as strong as their Northern Hemispehre counterparts.

Separating the occurrence of blocking by ENSO and PDO showed that the +PDO epoch interannual variability in the occurrence, duration, and BI were similar to those found in [1] as expected. In the Southern Hemsiphere the interannual variability was the same in the –PDO epoch albiet with increases in occurrence, duration, and days. But, within the Pacific Region, the relative occurrence of East Pacific blocking was greater in La Nina and Neutral years than during El Nino years for the +PDO epoch. The opposite occurred during the –PDO phase. In the Northern Hemsiphere, the interannual variability of these characteristics was opposite during the –PDO epoch. Finally, an examination of the occurrence of simultaneous blocking events was greater with a greater frequency in blocking occurrence, supporting the conjecture of [1].

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Table X. Character of Northern Hemisphere blocking events per year by region (ATL/PAC/CON) as a function of ENSO and PDO. The number of years in each category is shown in parenthesis.

+ PDO	Occurrence	Duration	Days	Intensity
El Nino (6)	12.8/5.8/4.8	8.4/7.7/8.1	107.3/45.1/39.1	3.43/2.55/2.65
Neutal (15)	12.1/6.3/6.1	8.4/7.8/8.2	101.0/48.9/49.9	3.46/3.44/2.67
La Nina (2)	12.5/9.5/8.5	9.4/7.2/7.9	117.8/68.2/67.5	3.25/3.41/2.57
Total (23)	12.3/6.4/6.0	8.5/7.7/8.2	104.1/49.6/48.6	3.43/3.23/2.65
- PDO	**Occurrence**	**Duration**	**Days**	**Intensity**
El Nino (7)	16.3/12.3/8.4	10.5/8.7/9.2	170.3/106.6/77.1	3.33/3.16/2.64
Neutral (12)	16.5/11.4/9.5	10.4/9.7/9.2	170.9/111.1/87.6	3.19/3.23/2.50
La Nina (8)	13.6/8.4/7.1	8.8/8.3/7.9	119.4/69.5/55.9	2.91/3.04/2.28
Total (27)	14.9/10.3/8.2	10.4/9.5/9.2	155.5/97.6/75.5	3.27/3.19/2.52

Table XX. Character of Northern Hemisphere blocking events per year by season (Su/F/W/Sp) as a function of ENSO and PDO. The number of years in each category is shown in parenthesis.

+ PDO	Occurrence	Duration	Days	Intensity
El Nino (6)	4.5/5.5/5.7/7.8	7.4/7.8/10.2/7.4	33.3/42.9/57.7/57.7	2.16/3.63/3.71/2.52
Neutal (15)	5.1/4.9/7.5/6.9	7.1/8.6/8.4/8.5	36.5/41.8/62.9/58.7	2.17/3.62/4.09/2.77
La Nina (2)	5.0/5.5/7.5/12.5	8.7/8.3/9.7/7.3	43.5/45.8/72.8/91.5	1.94/3.83/4.16/2.48
Total (23)	5.0/5.1/7.0/7.7	7.3/8.3/8.9/8.0	36.3/42.4/62.4/61.3	2.14/3.65/4.01/2.68
- PDO	**Occurrence**	**Duration**	**Days**	**Intensity**
El Nino (7)	8.9/8.3/10.1/9.7	8.9/9.2/10.0/10.1	78.4/76.1/101.8/97.8	2.36/3.58/3.70/2.80
Neutral (12)	8.0/8.8/9.5/11.2	10.7/9.7/9.8/9.5	85.6/84.9/93.2/106.2	2.32/3.39/3.81/2.66
La Nina (8)	5.8/6.6/8.8/8.6	9.0/8.2/8.5/8.2	51.8/54.2/74.6/70.7	2.18/3.21/3.35/2.39
Total (27)	7.2/7.7/9.1/9.6	10.3/9.5/9.9/9.7	73.7/73.5/89.8/93.5	2.33/3.49/3.76/2.68

Table Y. Character of Southern Hemisphere blocking events per year by region (ATL/PAC/IND) as a function of ENSO and PDO. The number of years in each category is shown in parenthesis.

+ PDO	Occurrence	Duration	Days	Intensity
El Nino (5)	0.4/7.8/0.8	6.8/7.1/6.6	2.7/55.6/5.3	2.19/3.04/2.95
Neutal (15)	1.1/7.7/0.7	6.0/7.2/7.0	6.4/55.4/5.2	2.91/2.72/2.98
La Nina (2)	0.5/5.5/0.0	8.0/6.6/0.0	4.0/36.2/0.0	1.84/3.10/NA
Total (22)	0.9/7.5/0.7	6.2/7.2/6.9	5.3/53.7/4.7	2.76/2.66/2.98
- PDO	**Occurrence**	**Duration**	**Days**	**Intensity**
El Nino (8)	1.6/10.9/2.3	6.0/8.8/8.4	9.8/95.9/18.9	3.33/2.97/2.74
Neutral (10)	1.7/12.3/2.5	6.1/8.3/6.7	10.4/102.1/16.7	2.63/2.83/2.52
La Nina (8)	1.1/9.0/1.9	7.1/6.9/7.6	7.9/62.1/14.2	2.88/3.02/2.62
Total (26)	1.5/10.8/2.2	6.3/8.3/7.4	9.5/89.9/16.6	2.92/2.85/2.62

Table YY. Character of Southern Hemisphere blocking events per year by season (Su/F/W/Sp) as a function of ENSO and PDO. The number of years in each category is shown in parenthesis.

+ PDO	Occurrence	Duration	Days	Intensity
El Nino (5)	0.8/3.4/3.6/1.2	6.0/7.0/7.6/6.0	4.8/23.8/27.4/7.2	2.28/3.23/3.11/2.48
Neutal (15)	0.9/3.4/3.3/1.9	6.0/7.3/7.3/6.5	5.2/24.9/24.2/12.2	2.34/2.85/2.80/2.74
La Nina (2)	2.5/1.0/1.0/1.5	5.9/8.5/6.8/6.8	14.8/8.5/6.8/10.2	2.71/3.55/3.93/2.26
Total (22)	1.0/3.2/3.2/1.7	6.0/7.3/7.3/6.5	6.0/23.1/23.4/10.9	2.33/2.77/2.83/2.54
- PDO	**Occurrence**	**Duration**	**Days**	**Intensity**
El Nino (8)	1.8/5.1/4.6/3.3	7.1/8.7/9.2/7.8	12.4/44.7/42.7/25.5	2.89/3.21/3.01/2.47
Neutral (10)	1.9/5.5/6.2/2.9	6.6/7.8/8.2/7.7	12.4/42.8/50.8/22.4	2.85/2.84/2.86/2.41
La Nina (8)	2.1/3.9/3.3/2.8	7.0/8.0/7.2/7.7	14.9/31.1/23.5/21.2	2.88/2.95/2.60/2.44
Total (26)	1.9/4.9/4.8/3.0	6.9/8.1/8.3/7.8	13.2/39.8/40.0/23.0	2.87/2.99/2.86/2.44

Appendix A

The top ten longest lived blocking events in the Northern Hemisphere (top) and Southern Hemisphere (bottom) from 1968 – present.

Rank	Event	Days	Region
1.	June 2003	35.0	Co
2.	December 2016	33.5	AR
3.	December 2010	33.0	AR
	May 2013	33.0	PR
	July 2013	33.0	PR
6.	December 2002	32.5	AR
7.	July 2003	32.0	Co
8.	February 2005	31.5	AR
9.	February 2005	31.0	AR
10.	May 2014	29.5	Co
Rank	**Event**	**Days**	**Region**
1.	July 2015	28.0	IN
2.	July 1976	26.0	PR
3.	May 2016	25.0	PR
4.	June 2005	22.5	PR
5.	May 2008	21.0	PR
6.	May 1973	20.5	IN
7.	August 2004	20.5	PR
8.	June 1981	20.0	PR
9.	June 2012	20.0	PR
10.	May 2009	19.5	PR
	October 2010	19.5	PR

Appendix B

The top ten stongest (BI) blocking events in the Northern Hemisphere (top) and Southern Hemisphere (bottom) from 1968 – present.

Rank	Event	BI	Region
1.	February 1991	6.42	PR
2.	March 1996	6.40	PR
3.	November 1997	6.31	AR
4.	March 1989	6.20	PR
5.	January 1985	6.17	PR
6.	December 1996	6.16	PR
7.	Janaury 1979	6.09	PR
8.	February 1975	6.08	AR

	December 1983	6.08	PR
10.	Janaury 2008	5.99	AR

Rank	**Event**	**BI**	**Region**
1.	July 2006	5.46	PR
2.	October 1995	5.40	AR
3.	May 1991	5.30	PR
4.	May 2016	5.08	PR
5.	September 1996	5.00	PR
6.	July 2016	4.85	PR
7.	June 1995	4.83	PR
8.	June 2005	4.80	PR
9.	May 2000	4.71	PR
10.	June 2007	4.68	PR

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