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Review

Atmospheric blocking events: a review

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Even though meteorologists have been aware of atmospheric blocking for more than 100 years, it is a phenomenon still not well forecast or completely understood. Also, while there is not one standard accepted definition, there are some commonalities known about the understanding of blocking behavior. Blocking occurs less often than other destructive phenomena, but globally their occurrence has increased since the beginning of the century. The longevity of blocking means it can negatively impact agricultural and economic activity and human comfort by bringing extreme conditions not only to the areas where they occur but also to locations well upstream and downstream. Additionally, while it is known where blocking occurs and their general character has been well described, operational models still struggle to replicate the intensity and duration even though improvement has been noted in the timing and location of onset. Climatologically, models still underestimate their occurrence. In the last 40 years, investigators have used case study analysis and numerical and theoretical models to understand the onset and maintenance of blocking. Comparatively few have examined block decay. This review endeavors to cover the highlights of the history of blocking investigations, especially in the last few decades, in order to provide an understanding for a more general scientific audience.

Keywords: atmospheric blocking; general circulation; climatology; dynamics; synoptic meteorology

Introduction

Blocking anticyclones have been recognized as a significant atmospheric phenomenon for over a century.[1] During that time, blocking was acknowledged as a large-scale disturbance (high pressure at the surface) that persisted for a long period of time in the middle and high latitude flows. These events were described as propagating very slowly, or even retrograding. The interest in these persistent anticyclones at the beginning of the 20th century was mostly in the context of long-range forecasting applications.[2,3] The name "blocking" probably describes the tendency for these anticyclones to block the regular progression of cyclones where they normally occur,[4] and Ref. 5 described the phenomena as "well-known" and "the most important in long-range forecasting applications."

Few studies highlighting the climatology or the dynamics of blocking events can be found in the literature prior to 1950. One of the first climatologies of "blocking action" was published by Elliot and Smith.[6] This work defined blocking as a persistent surface high pressure anomaly that exceeded a certain climatological threshold (+20 hPa) for a long period of time. They noted that there were preferred regions for blocking action, as well as interannual and even interdecadal variability in their occurrence from 1900 to 1938.

During the 1940s, with the more widespread use of upper air observations, researchers recognized that blocking events were quasibarotropic and that many relatively stationary persistent surface highs were also associated with a strong high-pressure cell aloft.[4–9] The former study[4] examined the propagation speed of long waves observationally, noting

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that there was a certain class of waves that approximated stationarity or retrograded in concert with the Rossby wave formula. The next year, Rossby[5] examined the dynamics of blocking and postulated that blocking is the effect of the "convergent distribution" of group velocity in long quasistationary waves.

Then, Yeh[9] theorized that blocking can be explained via the slow energy dispersion of an initial solitary wave and this supported the conclusion that blocking is a high-latitude phenomenon whose intensity and persistence increased with latitude, while the propagation speed decreased with latitude. This paradigm has been supported by other studies, including the relatively recent work of Luo,[10] who noted that the role of baroclinic synoptic-scale eddies is to transform the blocking event from a dispersive to a nondispersive system during onset. The opposite would occur during decay. Additionally, recent studies[11,12] have discussed the onset and maintenance of blocking in terms of the convergence of wave activity flux, and the latter study placed their view into a more modern context (a "traffic jam" in the jet stream).

Even though Rex[7,8] established the first (subjective) blocking criterion for upper air flow and likened blocking to a hydraulic jump in fluid flows, nonetheless, to this day, there is no one universally accepted criterion for what defines blocking.[13] The Rex criterion defined blocking as a "split" in upper air flow that persisted for 10 days or more. This study demonstrated that blocking events were prominent downstream of the Asian and North American continents as well as the associated storm tracks.

There are several classes of criterion that have been used historically to describe blocking events; however, there is now at least a common understanding of what constitutes a blocking anticyclone. Today, most studies define blocking as persisting for a minimum of 5 days, or long-lived with respect to the phenomenon (cyclones) that these events are impeding.[14] Ref. 13 reviews three of the most common types of blocking criterion: (1) the zonal index type,[15,16] (2) the thresholding type,[6,17] and (3) potential vorticity.[18,19] While Ref. 13 demonstrates that each index has features that recommend its use, the potential vorticity type identifies fewer events in general, while the thresholding types identify more events. When directly comparing each method, each criterion may not identify the same features simultaneously or detect the same features of the block. However, each does yield similar climatologies.[13]

Arguably, the zonal index type blocking criterion is the most frequently used today, whether the criterion examines the one-dimensional 500-hPa height gradients[15] following directly from the zonal index developed by Rossby[20] and modified by Namias,[21] or a two-dimensional index.[16,22] Even the potential vorticity indexes cited above would fall into the one- or two-dimensional category.

The typical blocking characteristics examined traditionally are occurrence, duration, and, occasionally, size. Block intensity (BI) is a metric that was first proposed by Lupo and Smith[23] and then automated by Wiedenmann *et al.*[24] and is based on the midlatitude 500 hPa height gradient in the vicinity of the blocking event. This quantity is also related to such dynamic quantities as enstrophy and entropy.[25] Another type of 2D index to include intensity was developed by Mokhov,[26] which is the area integral of the local gradient representing the region of the blocking system (center and surroundings). This quantity will have units of the product of energy and time and can be summed up through the lifecycle of the blocking event (and then summed up by region and season). Mokhov[26] referred to this index as an integral action or intensity index.

Review articles of blocking have appeared previously in the literature (e.g., Ref. 27). A recent review of atmospheric blocking and the response of blocking to climate change was published by Woollings *et al.*[28] This work primarily focused on the ability of models to represent blocking and then project the future occurrence of blocking under different climate-change scenarios by the end of the 21st century. This review will focus on aspects of blocking including (1) climatological character and variability, (2) observational studies and extreme weather, (3) theoretical studies, and (4) modeling studies. These will discuss the historical as well as the current paradigms regarding the nature of blocking anticyclones.

Climatological aspects of atmospheric blocking

Compared with many atmospheric phenomena, blocking (Fig. 1) is not well known among the general public because of the tendency for these events

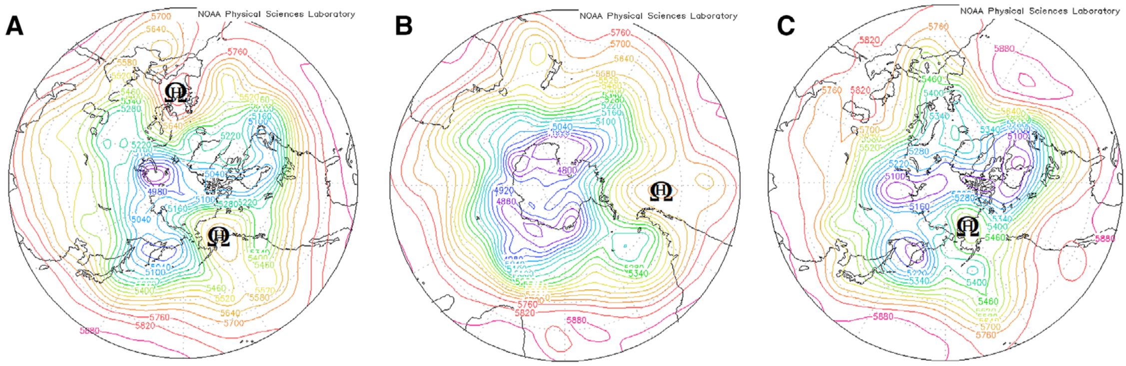

Figure 1. **Examples of blocking anticyclones on a 500-hPa height map for (A) 1200 26 February 2019 (omega block, Pacific region), (B) 1200 UTC 3 September 2019 (dipole block), and (C) 1200 UTC 9 November 2019 (Rex block). Panels A and C are from the Northern Hemisphere, while panel B is from the Southern Hemisphere. Atmospheric blocking events are marked with a Greek omega over an H. The contour interval is 60 meters.**

to occur primarily over the oceans, and in recent years, they occur only 50–60 times globally compared with more destructive and frequently occurring phenomena. In spite of the tendency to occur over the oceans, blocking often impacts large population centers because of their vast size and the fact that they persist for about 8–10 days.[29] Also, even though anticyclones are thought often to be quiescent phenomena, they can be associated with extreme weather conditions. Since the work of Refs. 6–8, there have been several climatological studies of blocking published since 1980 and it would not be possible to cite them all. These studies have used many different criteria, but there are some common findings among these climatologies.

In the Northern Hemisphere, blocking occurs primarily in three locations that correspond to the end of the climatological storm tracks[13,15–17,22–24] (but see also Refs. 26–36) (Fig. 2A). Furthermore, a recent study[36] used an idealized general circulation model and demonstrated that blocking maxima (minima) are located near stationary or standing high pressure (jet maxima) anomalies as well as the end (entrance) of the storm tracks. In particular, these regions are over the Pacific Ocean, especially east of the International Dateline to about 120°W; the Atlantic, from about 30°W to 60°E; and over Asia, near 90°E. Many of these climatologies specify the Pacific region as 140°E to 100°W, the Atlantic region as 80°W to 40°E, and the remainder as "continental" regions (Asia and North America). In the Southern Hemisphere (Fig. 2B), there have been comparatively fewer climatological studies[24,29] (but see also Refs. 37–40) and these demonstrate that the Pacific is the only active ocean basin (from 130°E to 120°W). All these climatologies agree blocking is comparatively rare outside of that region in the Atlantic and Indian Ocean regions. Lastly, Ref. 29 demonstrates that the primary blocking regions globally have changed little during the last 50 years.

When looking at other characteristics of blocking anticyclones, such as frequency of occurrence, duration, and intensity (Figs. 3 and 4, Table 1), some common behaviors of blocking are observed. Also, several references (e.g., Refs. 13 and 28, and references therein) discuss the common configurations for blocking flows based on the shape of the jet stream, for example, the "omega" block (Fig. 1A—Pacific), the "dipole" block (Fig. 1B), or the "Rex" block (Fig. 1A—Atlantic region and Fig. 1C; see also Ref. 28, anticyclonic and cyclonic wave breaking, respectively). However, examining blocking events over the course of their entire lifecycle would demonstrate that they frequently exhibit more than one of these configurations. Thus, this characteristic is not discussed here.

Most climatological studies find approximately 30–35 blocking events per year in the Northern Hemisphere (Table 1 and Fig. 3), and each persists for an average of 9 days. See also Ref. 29 and the 52-year record contained at the University of Missouri. This ranged from a minimum of 18 events to a maximum of 49 events in a year (Fig. 5). Earlier climatologies of blocking[15,23,30] found that blocking occurred most often in the winter and early spring, while they occurred least often during the summer

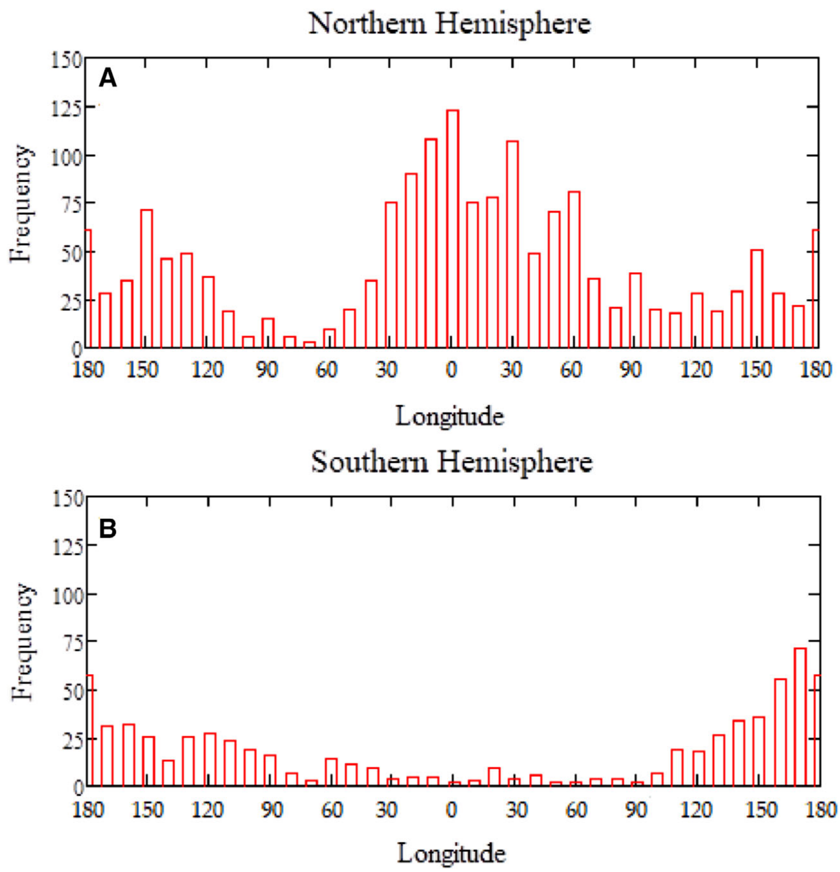

Figure 2. The frequency of block occurrence (ordinate) versus longitude (abscissa) for the (A) Northern Hemisphere and (B) Southern Hemisphere. Adapted and updated from Ref. 29.

and early fall (Fig. 4). This seasonality in blocking occurrence is due at least in part to the seasonal variation of cyclone frequencies in the midlatitudes given their dynamic connection, as discussed in Refs. 23 and 24 and as inferred from, for example, Ref. 41. The synoptic–dynamic connection will be discussed in the next section. Thus, these climatologies often described the blocking season as beginning in July, as in Ref. 29. Additionally, in spite of their relative infrequent occurrence, the longevity of blocking events means that they dominate the Northern Hemisphere flow for considerably more than one half of the calendar year.

These atmospheric blocking events have a mean intensity (BI) of 3.13 (Table 1 and Fig. 3) on a scale that varies from 1 to 7, with BI as formulated by Ref. 23. The BI was automated[24] by normalizing the central height value for the block at 500 hPa by the mean height gradient upstream and downstream of the blocking event. That number is then massaged such that the intensity scale varies as stated above, which is similar in concept to the numerical values used by the Saffir–Simpson Scale for hurricanes or the Enhanced Fujita Scale for tornadoes. The work of Ref. 24 shows that the quantity BI is related to the strength of that gradient, while Ref. 25 shows that BI is correlated to a quantity called integrated enstrophy (P = 0.10 or better). Enstrophy is a dynamic quantity related to fluid dissipation (e.g., Ref. 25 and references therein) and integrated enstrophy is also related to entropy (Kolmogorov–Sinai; see Ref. 25 and references therein). Summer season events are associated with the weakest BI (Fig. 4), while winter and fall season events are the considerably stronger than spring season blocking events. The duration of blocking does not vary appreciably (4%) by season in the Northern Hemisphere (Fig. 4), as suggested by the 50-year climatology of Ref. 29. However,

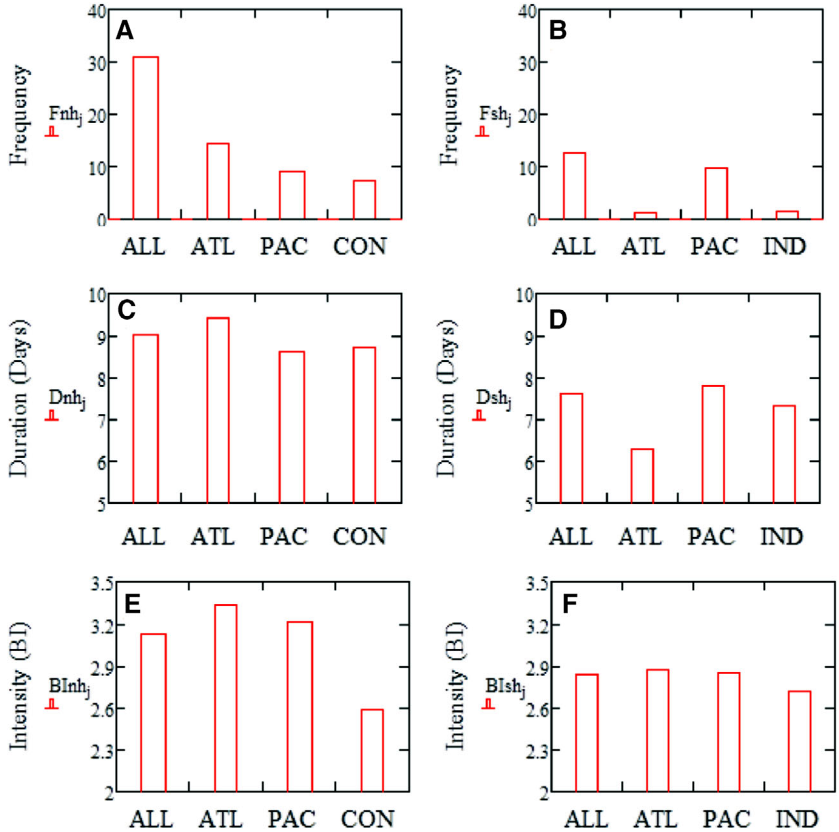

Figure 3. The (A and B) occurrence, (C and D) duration (days), and (E and F) intensity of blocking for (A, C, and E) the entire 52-year period for the Northern Hemisphere and each subregion and for (B, D, and F) the entire 50-year period for the Southern Hemisphere and each subregion. This is an extension of data from Ref. 29.

earlier studies, such as Ref. 24 (30 years) or Ref. 33 (55 years), found blocking events persisted for 17–33% longer in the winter season as compared with the summer season. It is possible that this is a function of the methodology used to detect blocking events, especially as concerns the latter study. Simultaneous blocking occurrences (e.g., two or more events occurring at once within the Northern Hemisphere; Fig. 1 left) occur during approximately 17% of the days in the year (Table 1). A positive correlation between BI and block duration, or BI and block size, was first identified by Ref. 23 and subsequent research[29,42,43] supports the idea that more intense blocking events are larger and persist longer. Additionally, Ref. 23 found a significant correlation between the deepening rate of upstream cyclones and BI.

Some climatologies[24,29,33,34,44] have examined the variation of blocking events with time in the Northern Hemisphere (Fig. 5A). The work of Ref. 24, which studied blocking in the late 20th century, suggested blocking was decreasing with time when comparing the 1980s and 1990s with earlier decades and studies. They also suggested block occurrence varied with respect to the El Niño and Southern Oscillation (ENSO) (Table 1). However, Ref. 29 revised this viewpoint as blocking has occurred more often since the turn of the 21st century. This study and Refs. 33 and 34 find little ENSO variability in the long-term record, while all three studies suggest that the late 20th century showed the distinct minimum in the late 20th century that[29] suggested could be linked to decadal variability associated with the Pacific Decadal Oscillation or the North Atlantic Oscillation (NAO) or their combination. Longer-term studies of blocking[33,45,46] show that blocking occurred more often in the early and mid-20th century. The latter two studies[45,46] link

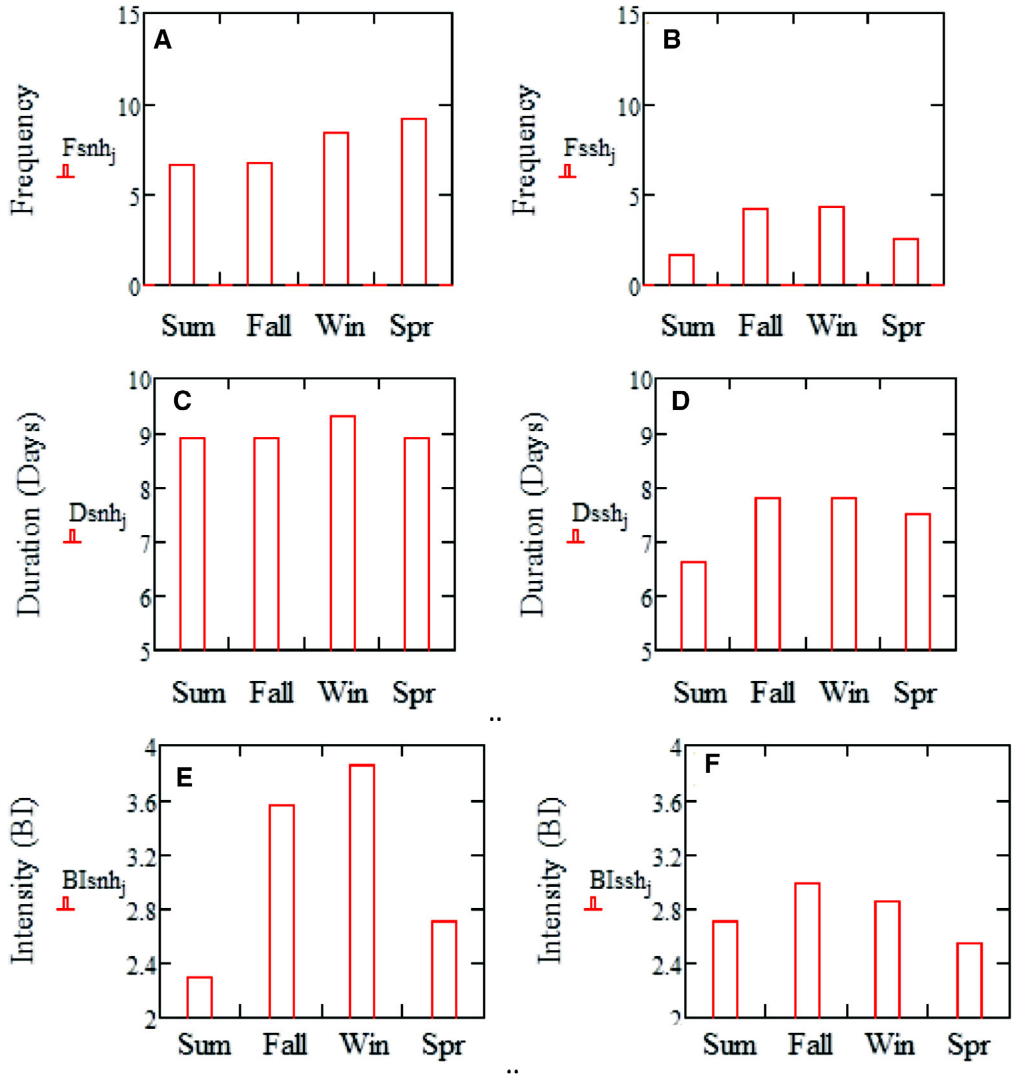

Figure 4. Seasonal statistics for the (A and B) occurrence, (C and D) duration (days), and (E and F) intensity of blocking for (A, C, and E) the entire 52-year period for the Northern Hemisphere and for the (B, D, and F) entire 50-year period for the Southern Hemisphere. This is an extension of data from Ref. 29.

this variability, at least in the Atlantic region, to the Atlantic Multidecadal Oscillation and the NAO.

Then, Ref. 29 also found that the lack of ENSO variability in the longer-term record reflects the fact that the interannual variability of the late 20th century was opposite to that of the early 21st century (Table 1). They also found that in the early 21st century, blocking events were longer lived, but weaker than their late 20th century counterparts. Trends as related to climate change are mixed,[28,46–49] and these studies suggest that changes in blocking frequency may overall reflect changes in where blocking occurs and the type of blocking index used.

Also, blocking has been shown to be linked to shorter-term (intraseasonal) variability, such as the Pacific North American (PNA) pattern,[50] the daily NAO Index,[51] and the Madden Julian (or Intraseasonal) Oscillation (MJO/ISO).[52,53] The work of Ref. 50 demonstrated that during the winter season, blocking was more prevalent in the central Pacific during the negative phase of the PNA pattern, although Refs. 54 and 55 suggested that the phase

Table 1. The characteristics of Northern Hemisphere blocking events per year as a function of ENSO and PDO

+PDO	Occurrence	Duration (days)	Intensity (BI)	% Simultaneous
El Niño (6)	23.5	8.1	3.06	7.6
Neutral (15)	24.2	8.2	3.26	8.9
La Niña (2)	30.5	8.3	3.11	12.7
Total (23)	**24.7**	**8.2**	3.20	**8.9***
–PDO	Occurrence	Duration (days)	Intensity (BI)	% Simultaneous
El Niño (8)	**38.1**	9.5	3.17	26.3
Neutral (12)	37.4	9.9	3.03	28.9
La Niña (9)	**31.3**	8.6	3.12	16.8
Total (29)	**35.7**	**9.4**	3.09	**24.4***

NOTE: The number of years in each category is shown in parentheses. Bold numbers show a statistically significant difference at $P = 0.10$; $^*P = 0.05$. These data are taken from Ref. 25 and updated.

of the PNA pattern (positive versus negative) influences where blocking is prevalent. Then, Ref. 51 (and many others) demonstrates that blocking is favored over the Atlantic (Eurasian) region during the negative (positive) phase of the NAO Index. The occurrence of blocking correlating to certain phases of the PNA pattern[56] or the NAO[57] is likely associated with the location of large-scale 500-hPa positive anomalies[36] since these indexes are based on the location of positive and negative anomalies (see Ref. 56). The MJO influences blocking across the Northern Hemisphere via the propagation of Rossby waves generated by tropical convection and radiating into the midlatitudes.[52,53] The results of Refs. 52 and 53 were consistent in spite of each study using a slightly different blocking index. Both of these papers show a decrease (increase) in blocking for the Pacific region, North America, the West Atlantic, and Europe associated with phases 1–5 (6–8) of the MJO.

In the Southern Hemisphere (Figs. 3 and 4, Table 2), roughly 10–15 blocking events occurred annually over a 50-year period from 1970 to 2019 and their duration was about 7–8 days annually. Their mean intensity was 2.84, which was significantly weaker (at $P = 0.01$) than those in the Northern Hemisphere. This is likely due to the fact that the Southern Hemisphere flow tends to be more zonal than the Northern Hemisphere flow. The seasonality of Southern Hemisphere blocking is more distinct in that fall and winter season blocking events (Fig. 4) occur more often, are longer lived, and stronger when measured using BI[29] compared with spring and summer events. This is consistent with the seasonality of Southern Hemisphere midlatitude cyclones as well.[41] In the Southern Hemisphere, the Pacific region (130°E to 60°W) is associated with the most frequent, persistent, and strongest block occurrences (Fig. 3). Only about three blocking events annually will occur within the Atlantic (60°W to 30°E) and Indian Ocean (30°E to 130°E) regions combined. Because of the infrequent occurrence of blocking outside of the Pacific region, simultaneous blocking events are observed only about 10 days (2.8%) of the year.[29] This study[29] also found that there is a strong correlation in both hemispheres between the number of blocking days and the number of simultaneous events ($P \leq 0.01$). Thus, the more events that occur, the more likely there will be simultaneous events, and this point will be discussed in the next section as well.

The overall trend for blocking in the Southern Hemisphere (Fig. 5B) is similar to that of the Northern Hemisphere in that blocking decreased during the later 20th century to a relative minimum during the 1990s, and then increasing again during the early 21st century.[29] The duration of blocking events in the early 21st century increased as well, but there was no change in the intensity (BI). In this hemisphere, the interannual variability in relation to ENSO did not change over the 50-year time series and blocking was more frequent and stronger during El Niño years when compared with La Niña years (Table 2). The relative occurrences agree with the results of others cited here.[39,40]

Additionally, Ref. 29 split the Pacific region into the western (130°E to 160°W) and eastern zones (160°W to 60°W). The results of Refs. 29, 37, and 40

Table 2. The characteristics of Southern Hemisphere blocking events per year as a function of ENSO and PDO

+PDO	Occurrence	Duration (days)	Intensity (BI)	% Simultaneous
El Niño (5)	**9.0***	7.0	3.02	1.7
Neutral (15)	**9.5***	7.1	2.76	1.4
La Niña (2)	**6.0***	6.7	2.74	0.0
Total (22)	**9.0***	**7.1**	2.83	**1.3***
–PDO	Occurrence	Duration (days)	Intensity (BI)	% Simultaneous
El Niño (8)	**16.5***	8.2	2.89	4.6
Neutral (11)	**16.6***	7.7	2.85	4.3
La Niña (9)	**13.0***	7.6	2.71	2.8
Total (28)	**15.7***	**7.8**	2.84	**3.9***

NOTE: The number of years in each category is shown in parentheses. Bold numbers show a statistically significant difference at $P = 0.10$; $^*P = 0.05$. These data are taken from Ref. 25 and updated.

demonstrate that more blocking occurs traditionally in the western zone and these blocking events are weaker ($P = 0.10$).[29] These studies also show that there were relatively more blocking events in the eastern zone during La Niña years in the late 20th century; by constrast, during the early 21st century, the eastern zone showed fewer events during La Niña years. The result described here is consistent with variations in Southern Hemisphere teleconnectivity.[58] In both hemispheres, there is a correlation between the duration and BI for blocking as highlighted by Ref. 29, and stronger blocking events tend to live longer ($P = 0.10$).

Observational studies of blocking and extreme weather

While blocking anticyclones tend to be associated with cloud-free conditions, many studies have associated blocking with anomalous weather over the regions they exist in, as well as the upstream and downstream regions, because of their impact on the jet stream. Episodes of frequent blocking have been associated with such events as heat waves and droughts since the 1970s for mid- and high-latitude locations.[59–65] Some of these blocking events and episodes have even become mass casualty events recently, especially for the nations of Eurasia in 2003[12] and again in 2010,[66] as well as being the underlying cause of ecological disasters, such as large forest fires or adverse agricultural impacts.[67–70] There are indicators that the recent heat and drought of northern Russia and Siberia have been associated with blocking, including the measurement of 38 °C (100 °F) in Verkhoyansk on June 20, 2020 (see the University of Missouri blocking archive[71]).

However, a wide range of other types of extreme weather events have been attributed to the blocking environment, such as cold waves,[46,47,63,72–75] extreme precipitation and flooding,[76,77] summer season thunderstorm activity,[78] blizzards,[79,80] as well as having an impact on the weather for entire seasons.[75,80,81] Within the last two decades, atmospheric blocking has also been shown to affect air masses and air mass transport across the globe in the troposphere,[82] as well as the stratospheric weather (sudden stratospheric warming or variability, e.g., Refs. 83–86), including photochemistry in this part of the atmosphere.[87] Additionally, because of the strong stability associated with blocking anticyclones in the lower troposphere, these events have been associated with the trapping of pollutants in urban areas when they occur, most notably Moscow in 2010[66] and the cities of eastern China.[88]

Blocking is also implicated in the steering of extratropical[89] and tropical cyclones, such as Hurricane Sandy (2012), which did not recurve out into the Atlantic Ocean, but instead tracked into the Atlantic Coast, and then inland. Blocking over the North Atlantic was present during this time.[71] Tropical cyclones taking this kind of path are not completely unknown, but this event provided a good example of how blocking can influence the path of tropical cyclones.[90] Conversely, studies, such as Ref. 91, demonstrated that recurving West Pacific typhoons will often transition to strong or explosively deepening extratropical cyclones that can then be linked to the onset of downstream blocking,

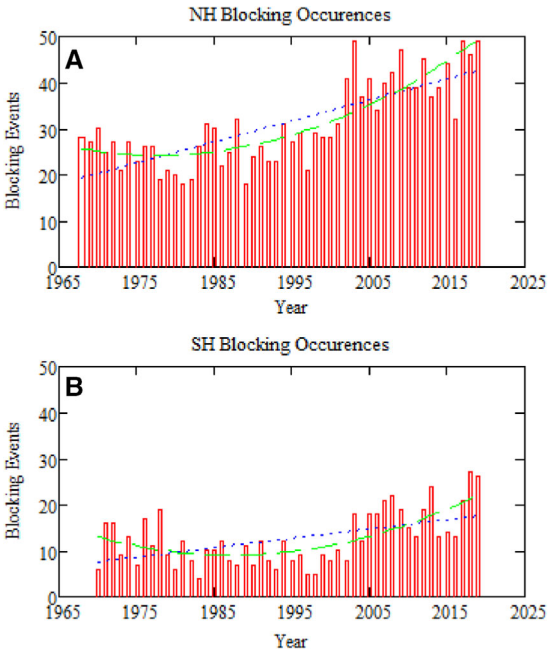

Figure 5. The occurrence of blocking with time for (A) the Northern Hemisphere and (B) the Southern Hemisphere. The blue dashed line is a linear trend line, while the green dashed line is a quadratic fit. Adapted and updated from Ref. 29.

and the powerful Typhoon Nuri in November 2014 is a striking example.[92] The study of Ref. 89 showed the influence of blocking on the path of extratropical cyclones along the east coast of the United States since these events may have a strong societal impact, depending on the propagation speed and intensity of extratropical cyclones. This study also reviewed the abundant literature on this topic.

The studies cited above discuss the impact of blocking on the character of weather and climate either as singular events or cumulatively via blocking episodes. However, many observational studies over the last 40 or more years have attempted to explain the onset, maintenance, and decay of individual blocking events. Even before this time, it was suggested that it was the repeated action of shorter waves in the large-scale flow,[5,6] and theoretical models of this process will be discussed in the next section. Early studies focused mainly on large-scale baroclinic forcing and topography[93,94] or resonant longwave amplification.[95] Some of these early studies[96,97] described blocking character as being consistent with that of solitary waves or "modons," which in their simplest form exist as a high–low vortex pair. These studies are still performed.[98,99] But at the same time, many studies viewed blocking as a scale-interaction problem, or as the interaction between synoptic-scale cyclones and large-scale anticyclones.

During the 1980s, it became fashionable to examine the lifecycle of individual cyclone events in order to determine how they behaved observationally and in a weather model, and to understand how weather forecasting could be improved. At the same time, similar studies were performed with blocking events and for similar reasons. Some studies examined the atmospheric potential and kinetic energy budgets associated with blocking.[100–102] However, given the difficulty in forecasting blocking just a few days ahead,[16] even today,[103] many have examined the onset of blocking and associated precursor rapid cyclogenesis.[23,104] These studies stated that all blocking events are preceded by developing cyclones and Ref. 23 showed that there was a correlation between cyclone deepening rate and BI ($P = 0.10$). Many determined that a favorable relationship between the developing upstream cyclone and a large-scale quasistationary ridge was needed at block onset.[104–109]

The work of Ref. 106 examined the nature of the synoptic scale contributions and was the first study to focus on the role of the concomitant deepening of a precursor synoptic-scale cyclone, the enhancement of an upstream jet maximum, and the onset of blocking (Fig. 6). During this process, a short-wave trough associated with the upstream cyclone also amplifies and phase-locks with the quasistationary downstream large-scale ridge. The enhancement of the jet maximum aids the transport of anticyclonic vorticity[106,107] or low potential vorticity air[110,111] into the block region, and the process is analogous to upstream jet maxima that enhance troughing.[112] Studies, such as Refs. 110 and, later, 12, 109, 113, and 114, acknowledged the repeated action of individual cyclone–block interactions in maintenance. The work of Ref. 115 extended the model of Ref. 106 to the entire lifecycle of blocking events. Lastly, it was studies such as these[12,115] and the climatological studies of, for example, Refs. 15 and 29 (see above) that determined that the onset and maintenance of blocking is a local process rather than a global one. Conversely, Ref. 116 noted that there is still a discernable role for the large scale in the support of simultaneous Northern Hemisphere

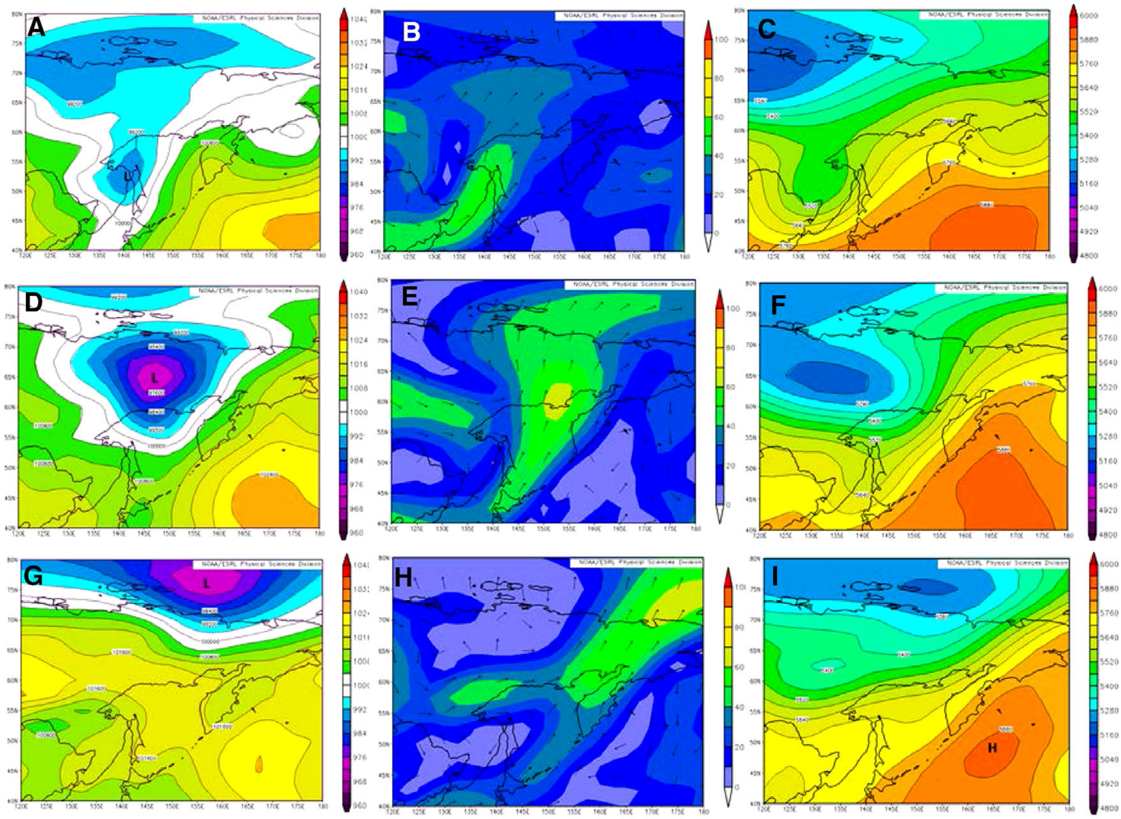

Figure 6. The (A, D, and G) sea-level pressure (Pa), (B, E, and H) 300-hPa vector wind (m s^{-1}), and (C, F, and I) 500-hPa height (m) for (A–C) 1200 UTC 25 August, (D–F) 1200 UTC 26 August, and (G–I) 1200 UTC 27 August 2016. The contour interval for sea-level pressure, vector wind, and height is 4 hPa, 10 m s^{-1}, and 60 m, respectively. Adapted from Ref. 103.

blocking events that may occur in both the Atlantic and Pacific regions.

Studies such as[106] that endeavored to examine case studies of blocking used diagnostic equations, such as the height tendency equation, the omega (vertical motion) equation,[107] potential vorticity equation,[110,111,117,118] the thermodynamic equation,[112,119] or a vorticity equation.[115,120] Many examined the role of the planetary-scale flow versus the synoptic-scale using case studies by partitioning the primary variables into these components. This will result in an interaction component in product terms. The results of Refs. 113 and 115 suggested that the synoptic scale was more prominent in Pacific region blocking, while the planetary scale was more dominant in the Atlantic region. Both of these works, as well as Ref. 107, suggested a prominent role for the scale-interaction terms and process in the Northern Hemisphere.

The work of Refs. 108 and 118 examined Southern Hemisphere blocking, and the large- and synoptic-scale features as well as their evolution were similar to their Northern Hemisphere counterparts. Both of these studies suggested qualitatively[108] and quantitatively[118] that the synoptic-scale contribution was dominant in the Southern Hemisphere cases. This is more similar to the Pacific region events of the Northern Hemisphere. The last key result from Ref. 118 was that the planetary–synoptic-scale interactions were important for the formation and maintenance of Northern Hemisphere blocking and thus the interaction between the waves was synergistic and nonlinear. In the Southern Hemisphere, the interaction term was small or negative, suggesting that blocking here may be the result of the superposition of scales. This may explain why blocking is shorter lived in the Southern Hemisphere.

The decay of blocking events is more complicated, as it has been related to the breakdown or changes in the large-scale flow,[119] or the unfavorable alignment of the processes described for block onset,[117] the lack of synoptic-scale support,[112,115,118] or a combination of these. Lastly, the role of the diabatic process in blocking has been recognized for a long time, but there are relatively few studies of highlighting this process. This was elucidated early on with the role of surface heating from the underlying oceans,[121] as such heating contributed to the formation of a block. Recently, the role of land–surface heat fluxes[122] has been shown to play a role in the maintenance of blocking, and the role of surface fluxes on BI[123] has been demonstrated. Additionally, the role of latent heating in enhancing directly or indirectly block formation and maintenance[124,125] by strengthening the upstream synoptic-scale eddies has been studied as well.

An elegant synoptic-dynamic approach to examining the physics of blocking was proposed by Ref. 18 and used the potential vorticity approach to describe Rossby wave breaking[126–130] as the mechanism that generates and maintains blocking in both the Northern and Southern Hemispheres. As stated in Refs. 131 and 132, Rossby wave breaking (Fig. 1A and C) is the key process leading the meridional reversal of the midtropospheric height and the upper atmospheric potential vorticity gradients associated with blocking. This overturning is accompanied by the poleward (equatorward) flux of low (high) potential vorticity air.[131] The work of Ref. 132 proposed that blocking could be classified by the orientation of wave breaking (cyclonic and anticyclonic) and the intensity of the warm or cold air mass extrusion associated with the potential vorticity field and the blocking event. They also found that particular configurations for wave breaking dominate over different regions of the globe.

Theoretical studies of blocking

Theoretical and dynamic-based studies of blocking began in earnest in the 1940s when the use of upper air data became more widespread. For example, Ref. 4 examined the propagation speed and development of upper air long waves and used the Rossby wave equation in order to verify that long waves obeyed this relationship. They noted that blocking could be described as "unexplained" disturbances that were either stationary or moved slowly westward and whose dimensions were consistent with those suggested by the Rossby formula. Then, Rossby himself[5] described blocking action as group velocity convergence in long quasistationary waves, in which the zonal flow weakened, resulting in an increase in meridional energy. He defined the meridional energy as proportional to vorticity, and called this quantity intensity as well. This suggests the repeated action of shorter waves supported blocking, and this action was even hinted at by Ref. 1. Ref. 9 was the first to discuss blocking in the context of a solitary wave, and later studies (e.g., Ref. 10) would discuss the large or planetary-scale component of blocking as a Rossby soliton or dipole blocking. Around the turn of the 21st century, Refs. 10 and 11, and others have found success replicating the synoptic and large-scale interactions described above and these will be highlighted below.

The proliferation of these simple primitive equation (PE) model–driven studies began with Ref. 93, which examined blocking in a barotropic channel model on a beta plane with topography. They developed a low-order model similar to that of Refs. 133 and 134 using conservation of potential vorticity and which contained a vorticity source and sink. They found multiple equilibria in their model as linked to the resonance between large-scale waves and topographic forcing, including an analog for blocking. However, this theory does not explain the onset, maintenance, and decay of blocking or the connection to synoptic-scale cyclones highlighted above. Additionally, Ref. 36 suggests that topography is important for the occurrence of blocking but not the location or movement of blocking. Nor does this theory describe the dipole blocking configuration suggested in other studies.[10,95,96] Early studies that portrayed blocking as dipole, such as Refs. 95 and 96, can describe adequately the large-scale structure of blocking. However, these studies failed to represent the key properties of blocking such as the interaction with synoptic-scale eddies in observed events that can be associated with the onset, maintenance, and decay of blocking (e.g., fluctuations in intensity[112,115]). Studies, such as Refs. 10, 98, and 114, do represent these interactions.

Shortly after Ref. 93, similar models were developed,[95–97,135–139] of which the most well-known was Ref. 138. These models were among the first to represent blocking as the result of large- and synoptic-scale interactions using PEs. The study of Ref. 138 proposed the "eddy straining hypothesis" as the support mechanism for blocking. Their model proposed that smaller scale eddies were stretched and deformed on the westward side of a large-scale split flow region (similar in configuration to Fig. 1B), and this could support the dipole through the transport of low (high) potential vorticity into the anticyclonic (cyclonic) vortex. In Ref. 138, the large-scale split in the channel model jet stream would approximate a blocking dipole (poleward high and equatorward low), and the barotropic vorticity equation with a smaller scale wavemaker the upstream cyclone. These studies inspired the observational studies such as Refs. 104–109 in the previous section. However, Ref. 140 demonstrated using a similar model that the eddy straining hypothesis may not be as effective as many studies have found since they show the effectiveness of this hypothesis is sensitive to the properties of the "synoptic"-scale waves as well as the large-scale component or basic flow. Furthermore, Ref. 128 suggests that the eddy straining mechanism is a result of block onset rather than the cause. This study suggested that preexisting synoptic-scale eddies are needed to explain or represent the lifecycle of blocking.

It was proposed by Refs. 136 and 137 that blocking can be described as a rapidly intensifying or amplifying eastward propagating wave that initially emerges from a three-dimensional flow due to a combination of barotropic and baroclinic processes. The work of Ref. 137 further elaborates that the scale of this disturbance grows in scale and becomes stationary. Then, the wave amplifies without propagating eastward and the equivalent barotropic forcing becomes dominant. They[137] described this mechanism as a three-dimensional instability that results in the unification of Refs. 92 and 95 with Refs. 96 and 97. However, this work did not adequately capture the synergistic synoptic- and large-scale interactions that are important to block formation and maintenance, and they did not investigate block decay.

More complex PE models were developed by the late 1990s and using the barotropic vorticity equation on a sphere which contained low- (standing) and high- (transient) frequency forcing and their interactions.[113] Studies such as these suggested that the low-frequency component was most important in the Atlantic region, but the contribution from transient eddies could not be ignored. In the Pacific, the higher frequency transients were more important, with a secondary contribution from the low-frequency components. They compared their results with observations, and their model results confirmed those of observation studies of Northern Hemisphere blocking in the previous section. The next year, Ref. 141 demonstrated that changes in the large-scale flow associated with vacillation, as simulated in a channel model, contributed to the breakdown of blocking in spite of the presence of synoptic-scale forcing.

Later, as stated in Ref. 12, many of these models can describe the onset and maintenance of blocking, along with the important scale interactions, but none could define an onset criterion for blocking. Using a model similar to Ref. 93 (or their own previous work[11,113]), they were able to demonstrate that blocking could be formed if the local upstream transients developed strongly even if the initial state was nonblocked. This was due to the inclusion of a nonlinear (interaction) term in their model. This was supported by observations in Ref. 113 and also in Refs. 107 and 115, for example. They showed that the local wave action (LWA) (group velocity of Rossby waves × wave activity density in a reference state[11,12]) varied linearly with the zonal LWA flux, much as traffic flow will vary with traffic density. However, the contribution of the nonlinear interaction term is that when the Rossby waves grow, they will slow the zonal wind and limit the zonal LWA flux in a similar manner to how heavier traffic density will slow down traffic flow.

Additionally, a series of studies, beginning with Ref. 10 and then Refs. 142 and 143 and culminating with the nonlinear multiscale interaction model proposed by Ref. 144, carry blocking through the entire lifecycle of the event, which was a major step forward. These studies show that the large-scale self-interaction projected onto the synoptic scale plays a key role in block onset, while the scale interaction term is important after onset in a manner similar to the eddy straining. This is similar to the results obtained from observational studies.[106,107,115,118] The latest study[144] shows that during block decay, the planetary waves propagate upward in the region downstream of the block, a result that is consistent with observations.[82–87] Thus, while convergence of group velocity and its energy is the mechanism first proposed by Ref. 5, studies from the research groups of Refs. 12 and 144 have elucidated the nonlinear wave–wave interactions that take place during the onset and maintenance of blocking.

Modeling blocking events

A recent review article[28] examined the ability of weather and climate models to replicate the occurrence and duration of blocking anticyclones. Traditionally, models have underestimated the frequency and persistence of blocking.[19,145–149] Several reasons have been cited[28] for the models' shortfall in replicating blocking occurrence and persistence, including: (1) the ability of models to replicate the mean flow correctly,[16,145–151] and (2) model characteristics (e.g., resolution,[152–154] parameterization,[155–157] or the model dynamics[158]). This review article[28] also summed up the current research regarding the future of blocking in the 21st century. The main conclusion was that the confidence in future occurrences of blocking is low due to the differences in block detection methods (see also Ref. 159), model design, and model physics. However, Ref. 28 concluded that the models generally do agree that the frequency of blocking overall may decrease even if there may be changes in where and when blocking occurs. They also noted that these climate models struggle with the natural variability of blocking as well.[34,160] However, a new article[161] shows remarkable skill in replicating observed Atlantic region NAO and AMO variability using the Community Earth System Model–Decadal Prediction Large Ensemble (CESM-DPLE) at NCAR.

Since the occurrence of blocking is critically linked to the occurrence of extratropical cyclones, replicating the mean flow correctly with respect to the storm tracks is important.[151] This work[151] is one of the most recent articles to address the topic. Models have consistently underestimated the observed strength (intensity and/or number of cyclones) of the storm track as well as the location and the latitudinal tilt or orientation of this phenomenon (Ref. 151 and references therein). However, Ref. 151 shows that recent experiments using the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 6 (CMIP-6) suite of models improved over the previous CMIP-5 suite in representing the storm track character. However, the model storm tracks are still underrepresented with respect to observations. The tendency for models to underestimate the observed storm track character, as well as future scenarios demonstrating that the storm tracks weaken in a warmer world (e.g., CMIP-5[162]), would at least partly explain the overall decrease in future blocking occurrences cited by Ref. 28.

Additionally, the latest CMIP-6 results[163] demonstrate that the overall representation of blocking has improved since CMIP-3, but their occurrence is still biased toward fewer model blocking events in most regions and seasons. Ref. 163 suggests the CMIP-6 models are performing better in some parts of the world (e.g., North Pacific) and seasons (e.g., summer), but that some regions (e.g., Europe) and seasons (e.g., winter) still show large negative biases and/or no improvement in block occurrence. Lastly, this study[163] suggested that the occurrence of blocking would decrease in a warming climate consistent with Ref. 28. However, in some regions and seasons (e.g., the summer season, Ural and Asia regions), a greater number of more persistent blocking events are projected. These results are consistent at least in part with the underestimate of storm track character cited above.

While Ref. 28 reviewed the ability of models to represent and project blocking, and studies such as Refs. 34, 36, 54, 90, 91, 143, 165, and 166 examined various aspects of blocking using models, here the focus will be on operational predictability. One of the first studies to tackle the operational predictability of blocking was Ref. 16. When they published their work, they used the European Center for Medium Range Forecast (ECMWF) Model to demonstrate that block onset was missed consistently beyond 3–4 days before the observed onset regardless of whether they occurred in the Northern or Southern Hemisphere.[166] Conversely, once the blocking appeared in the initial condition, the medium range predictability was reasonable but underestimated. They also found that in the Pacific Ocean region, a more intense block was better forecast than a weaker event.

A decade later,[167] the situation was not much improved for operational model forecasts using a single model run, although Refs. 168–170 showed that ensemble prediction systems improved on the skill and lead time over the control simulation for anticipating blocking out to about 10 days. The decay of blocking events is also not well simulated, according to Refs. 16 and 171, since the persistence of blocking is not well forecast. The latter study used an ensemble system to study the blocking events associated with the deadly 2010 heat wave over Eastern Europe and Western Russia, although the same author[172] reported better success with anticipating block decay earlier.

Lastly, Ref. 103 examined the predictability of blocking using the operational Global Ensemble Forecasting System (GEFS). They chose blocking events representing warm and cold season cases as well as Atlantic and Pacific region cases. This study also examined the predictability of the intensity of blocking as measured using BI (see above). This study showed that the GEFS modeling system forecasts the onset location of blocking with lead times consistent with Refs. 168–170 for warm season and weaker BI blocking events. In Ref. 103, stronger blocking events were forecast with less lead time comparatively. The BI (BI—underestimated by 10% or more in the model) and duration were underforecast by the GEFS model system in their case studies, a result similar to that found in climate models.[160,163] The BI in Ref. 159 was approximately 5% less in their model. This work[103] attributed the underforecast of BI to the same issues highlighted in other models (e.g., forecasting mass gradients, cyclones, and model physics) by Refs. 28 and 151.

Summary and conclusions

This article is meant to provide a review of the history of the identification and understanding of the physical processes involved in the phenomenon called atmospheric blocking. While blocking is not a term commonly used in routine operational weather forecasts for the public or in media weather broadcasts, or by the general public, the increased attention to blocking in academic studies means the term *blocking* has appeared more frequently in modern news stories.[173–175] This review is by no means comprehensive; however, the goal was to highlight some of the major developments in our understanding of atmospheric blocking. A recent comprehensive review[28] of the ability of weather and climate models to represent blocking as well as how the occurrence of blocking may change in future climates was also published recently.

Blocking has been known to the weather community for over a century, and its importance in subseasonal and seasonal range forecasting was recognized early on and continues to this day.[109] However, the first studies describing the climatological behavior were performed closer to the middle of the 20th century, when upper air observations became more numerous. At that time, blocking was recognized to be a midlatitude, mid and upper tropospheric, quasistationary, and persistent phenomenon related to the dynamics of the jet stream. Before upper air observations, blocking was noted primarily by its surface reflection, but other surface anticyclones were also called blocking.

As described above, the occurrence of blocking can influence large sectors of the globe for long periods of time. While there is no one particular commonly agreed upon definition of blocking, today most researchers identify them as ridging in the jet stream persisting for 5 days or more. Also, the indexes used most often for the identification of blocking today are primarily the "zonal index-type," or as a reversal in the midlatitude height and potential vorticity gradient. Additionally, where blocking occurs primarily is well known. Today's climatological studies have also used some measure for intensity or strength as related to the midlatitude mass or potential vorticity gradients.[27] Additionally, current climatological studies are mainly devoted to refining our understanding of the interannual and interdecadal variability in both hemispheres as well as their tendency for change in the face of a changing climate.

Blocking has been associated often with the persistent occurrence of extreme temperature and precipitation regimes, including the impacts these might have on the occurrence of other atmospheric phenomena, on the environment, as well as on the social or economic well-being of modern societies. In the last four decades, a number of studies have examined the observed synoptic-scale evolution, the interactions with the large scale, as well as the atmospheric dynamics involved in the onset, support, and even decay of blocking during their lifecycles.

Additionally, simplified PE models, as well as complex weather and general circulation models, have been used to understand what atmospheric and surface processes drive the onset and maintenance of blocking. In the middle of the 20th century, theoretical models were first built to capture the large-scale appearance and physical properties of blocking, such as the impact of topography. However, each of these models also had their drawbacks as they could not capture some aspects of the physics associated with the entire block lifecycle, including the scale interactions. However, since the latter part of the 20th century,[138] and especially since the beginning of the 21st century, these simplified PE models have made substantial gains in representing the scale interactions[12,144] involved in the block lifecycle and the latter can even replicate block decay. More work needs to be done in order to understand block longevity and decay. In short, we can describe the formation and maintenance of blocking as a complex scale-interaction problem between upstream development of synoptic-scale waves and how they interact with the large-scale jet-stream ridge.

Lastly, studies have demonstrated that the predictability of blocking is still an open research question. While we have a better understanding of the onset dynamics and maintenance, operational forecast models continue to struggle with the timing of onset and decay. Ensemble modeling and then predicting the formation of blocking in terms of probabilities have shown some promise in extending the range of forecasting these events. The models perform reasonably well in predicting where blocking may occur. However, even to this day, weather and climate models tend to underestimate the duration and intensity of blocking, and these issues are rooted likely in the construction of the model itself as well as how well the model represents the general circulation. This is especially true as regards the ability of general circulation models to capture the character of the storm tracks and/or individual cyclone events (especially those that deepen more rapidly) since they contribute greatly to block lifecycles and intensity. Finally, improvements in modeling and predicting blocking have progressed continually, as shown in observational and the latest CMIP-6 results, but as is pointed out here and in many of our references, there is still more work to be done.

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Competing interests

The author declares no competing interests.

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