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TOWARD A COMPREHENSIVE DETECTION ALGORITHM FOR
ATMOSPHERIC BLOCKING EVENTS

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TOWARD A COMPREHENSIVE DETECTION ALGORITHM FOR
ATMOSPHERIC BLOCKING EVENTS

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Abstract

Atmospheric blocking is a phenomenon in which upper-level atmospheric flow becomes quasi-stationary for an extended period (i.e., several days to weeks), leading to some of the most impactful large-scale extreme weather events in the mid-latitudes including droughts, heatwaves, flooding, and cold air outbreaks. Although blocking has long been recognized, the physical mechanisms responsible for blocking formation, maintenance, and decay remain poorly understood, posing a challenge for improving long-range weather forecasts. A key obstacle in this effort is the ambiguity in how blocked flow patterns should be defined, resulting in the absence of a unified objective blocking detection algorithm. Using ERA5 reanalysis data, this thesis develops a novel objective algorithm to comprehensively detect and characterize blocking events in the Northern Hemisphere. Building upon established blocking identification metrics, the algorithm incorporates three-dimensional tracking to approximate the dynamic spatiotemporal evolution of blocked flow patterns. It also accounts for blocking diversity by classifying events into ridge and dipole flow patterns.

Applying this algorithm, a data set of Northern Hemisphere blocking events from 1950–2024 is established. The resulting climatology and trends of blocking characteristics are broadly consistent with previous studies that use alternative detection methods. The relationships between blocking and latent heating, as well as the influence of the El Niño Southern Oscillation and the North Atlantic Oscillation, are examined. These relationships exhibit notable differences from previous findings. Overall, the results suggest that a comprehensive blocking detection approach offers meaningful improvement over more simplified algorithms.

Chapter 1

Introduction

The most impactful large-scale extreme weather events in the mid-latitudes are often linked with persistent, largely unpredictable patterns in the jet stream known as atmospheric blocks. These are large, quasi-stationary longwave patterns that persist for long periods (i.e., several days to weeks) and disrupt the normal zonal flow of the jet stream, essentially locking it in place (Berggren et al., 1949; Elliot and Smith, 1949; Hoskins and D., 1987; Rex, 1950). During blocking events, flow is diverted into an elongated meridional orientation exhibiting a strong poleward anticyclone and at least one equatorward cyclone that generate stagnant weather patterns, often resulting in anomalous and occasionally extreme weather events in the mid-latitudes (e.g., Charney and DeVore, 1979; Masato et al., 2011; Rex, 1950). These include heatwaves, droughts, wildfires, and cold air outbreaks associated with persistent ridging (e.g., Biernat et al., 2021; Black et al., 2006; Fennessy and Kinter III, 2011; Gilbert, 2010; Lillo et al., 2021; Luo et al., 2016; Mass et al., 2024; Millin and Furtado, 2022; Neal et al., 2022) along with extreme precipitation associated with persistent troughing (e.g., Lenggenhager and Marius, 2019). Consequently, blocking events are one of the most impactful large-scale weather phenomena in the mid-latitudes, often resulting in substantial loss of life, economic damages, and weakening of infrastructure (García-Herrera et al., 2010; Gilbert, 2010; Shaposhnikov et al., 2014; Wegren, 2013; White et al., 2023). While these impacts have driven considerable research into blocking, the physical processes responsible for the formation, maintenance, and decay of these events are still largely

uncertain. One reason for this is the lack of a unified method for identifying and characterizing blocking events, limiting the ability to examine them accurately. This thesis addresses this issue through the development a novel blocking detection algorithm that comprehensively incorporates the spatiotemporal structure and evolution of blocking flow patterns. In examining the climatology of Northern Hemisphere blocking events identified via this algorithm, a flexible approach to blocking detection is established.

While the existence and impacts of atmospheric blocking patterns have been recognized since the mid-twentieth century (Rex, 1950), a comprehensive theory for the processes responsible for the life cycle of blocking events has not yet been developed, largely due to the extreme complexity of the dynamics related to blocking (Woollings et al., 2018). Blocking pattern development has been primarily associated with Rossby wave breaking events. These occur when poleward advection of low potential vorticity (PV) air and equatorward advection of high PV air amplifies the meridional meandering of the jet stream to the point that it begins to overturn, similar to how ocean waves collapse once they become too steep (McIntyre and Palmer, 1983). In cases that result in blocking, the poleward advection of low PV air is often abnormally strong, which rapidly forms intense overturning ridges that solidify into blocked anticyclones (Woollings et al., 2018).

Blocking patterns may be induced by a wide variety of forcing mechanisms. Interactions between the planetary background flow with Rossby waves or between Rossby waves of varying wavelengths have been associated with blocking onset (Austin, 1980; Brunet, 1993; Charney and DeVore, 1979; Legras and Ghil, 1985), and has been known to vary geographically (Burkhardt and Lupo, 2005; Nakamura et al., 1997). The migration of tropical waves into the mid-latitudes has also been observed to assist in blocking formation through interaction with the background flow (Hoskins and D., 1987; Renwick and Revell, 1999). Extended poleward transport of air from rapid cy-

clogenesis of slow-moving extratropical cyclones (Colucci, 1985; Rivière and Orlanski, 2007; Sanders and Gyakum, 1980), as well as interactions with transient storm systems (Gabriel and Peters, 2008; Masato et al., 2011) have also been linked with blocking onset. More recently, upstream diabatic heating processes have increasingly been shown to be an important factor in the amplification of blocking anticyclones (Crocì-Maspoli and Davies, 2009; Liu and Wang, 2025; Neal et al., 2022; Pfahl et al., 2015; Steinfeld et al., 2020; Steinfeld and Pfahl, 2019; Tilly et al., 2008).

Blocking maintenance is also influenced by a range of different factors. One mechanism is the ingestion of transient synoptic-scale anticyclonic eddies into the blocking anticyclone, which supplies the anticyclone with low potential vorticity necessary for sustained persistence (Austin, 1980; Benedict et al., 2004; Hwang et al., 2020; Mullen, 1987; Shutts, 1983; Yamazaki and Itoh, 2013). Teleconnections also serve a role, with intraseasonal (e.g., Madden-Julian Oscillation; Henderson et al., 2016; Moore et al., 2010), interannual (e.g., El Niño Southern Oscillation, North Atlantic Oscillation, Arctic Oscillation; Barriopedro and Calvo, 2014; Luo et al., 2008; McKenna and Karamperidou, 2023; Renwick and Wallace, 1996; Scherrer et al., 2006), and interdecadal (e.g., Atlantic Multidecadal Oscillation; Kwon et al., 2020) patterns observed to promote or suppress synoptic-scale wave breaking in the extratropics depending on phase. The two most common flow patterns are ridge blocks and dipole blocks (commonly referred to as omega and Rex blocks, respectively; Kautz et al., 2022; Liu and Wang, 2025; Woollings et al., 2018). Ridge blocks exhibit a central anticyclone that is flanked by two distinct cyclones to its south forcing the jet stream into a pattern resembling the Greek letter Ω (Fig. 1.1). Dipoles exhibit only one associated cyclone, forcing flow into a pattern resembling a comma. Diabatic heating processes have been observed to influence the maintenance of ridge and dipole blocks in opposite ways (Liu and Wang, 2025).

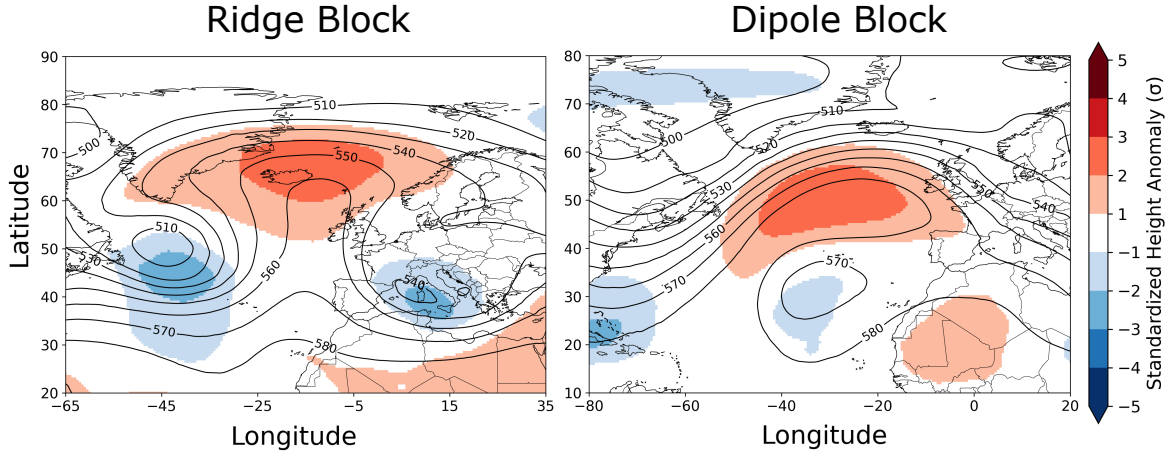


Figure 1.1: Maps of the geopotential height (line contours) and standardized geopotential height anomaly (shaded contours) compared to 1991–2020 climatology, for a ridge (left) and a dipole (right) block over the North Atlantic Ocean.

The subseasonal-to-seasonal (S2S) range (2–8 weeks), bridges the gap between short-term weather and long-term climate prediction (Hudson et al., 2011; Mariotti et al., 2018; White et al., 2017). It is notoriously difficult to provide accurate forecasts for this range, as initial conditions of the atmosphere become largely unpredictable by numerical models (Meehl et al., 2021), while primary sources of seasonal predictability (e.g., teleconnections, land-atmosphere interactions), are generally weak (Mariotti et al., 2018). Due to this, extreme weather patterns that may have long-term impacts are often not accurately forecast until just a few days in advance, severely limiting the ability for emergency managers to effectively mitigate associated damages. Because atmospheric blocking patterns exist on the S2S timescale and are associated with the development of large-scale extreme weather events, they are a valuable source of predictability. As such, the lack of a comprehensive theory for modeling the complex network of interactions responsible for blocking presents a major hurdle in the advancement of numerical modeling over the S2S range (Anstey et al., 2013; Matsueda, 2009). Thus, improving the predictability of blocking events is a principal objective

for modern climate dynamics research (Wang et al., 2026). However, studies in this area have been limited by considerable difficulties in defining which flow patterns can be considered blocks.

Due to the complexity of factors responsible for blocking patterns, blocking events rarely exhibit the same structure, nor do they maintain the same structure over their lifetime. As such, a singular definition for blocking often fails to capture the full range of impactful blocking patterns. When surveyed, experts in blocking research expressed different and sometimes opposing views on which flow patterns could be described as blocks (Wang et al., 2026). With such ambiguity, it is difficult to model the factors responsible for blocking formation and maintenance using a single identification metric. Over time, a multitude of objective blocking detection methods have been developed with the strategy of using single variables that are indicative of blocking flow patterns (Dole and Gordon, 1983; Schwierz et al., 2004; Tibaldi and Molteni, 1990). While this approach has resulted in objective algorithms capable of detecting blocks, each method produces substantially different blocking characteristics (e.g., frequency, spatial distribution, duration, etc.) than those of methods employing other variables (Pinheiro et al., 2019). Additionally, the ability to differentiate blocks by flow type is limited (i.e., ridge vs. dipole blocks; Liu and Wang, 2025; Sousa et al., 2021). As such, these methods have so far failed to satisfy the growing need for a unified blocking detection method that incorporates the full range of blocking diversity. To address this need, we seek to answer the following main research questions:

1. How can the dynamic spatial structure and temporal evolution of blocking patterns be represented in a blocking detection algorithm?
2. What are the characteristics (i.e., frequency, spatial distribution, duration, intensity, and size) of blocking events identified via our novel blocking detection

algorithm, and how do they compare with those detected via other algorithms?

3. How do the characteristics and trends of Northern Hemisphere blocking events vary across region, season and flow type?
4. How do associations between relevant physical processes (e.g., dynamical processes and interannual teleconnections) and blocking events identified via our blocking detection algorithm compare to those observed by studies employing other blocking detection algorithms?

Using ERA5 500-hPa geopotential height data and the blocking detection method developed by Tibaldi and Molteni (1990) as a basis for our novel algorithm, we integrate adaptations from multiple sources to extend the geographical scope for blocking identification, and implement additional filters for erroneously detected blocks. Additionally, three-dimensional mapping facilitated by the TempestExtremes framework (Ullrich et al., 2021) will allow for spatiotemporal tracking of blocked flow patterns. Also, following Liu and Wang (2025), we classify blocks into separate flow types. With our algorithm, a data set of blocking events in the Northern Hemisphere from 1950–2024 is created. The climatology and trends of characteristics exhibited by blocks detected via our algorithm (i.e., frequency, spatial distribution, duration, maximum spatial area, intensity) will be characterized. To contextualize our observations, we compare with studies employing similar blocking detection methods. Finally, associations with relevant dynamical factors and teleconnection patterns will be examined and compared to studies employing alternative blocking detection methods.

The primary goal is to introduce and demonstrate the merits of an approach to blocking identification that more comprehensively incorporates the spatiotemporal structure and evolution of blocking events than previous detection methods. Although most of the adaptations employed in this work are not new, they have not yet been

integrated into a single algorithmic process for blocking detection and characterization. In performing this novel integration, we produce a detection method in which the individual advantages of each adaptation combine to reduce the biases of the original detection method our algorithm is based upon, including a stringent filtering process for flow patterns mistakenly identified as blocks. In addition, we introduce a process for expanding the upper latitudinal bound of analyzed points to 90°N , which has not yet been employed in any blocking detection methodology (Burzdak et al., 2026). As a result, our algorithm is the first among detection methods derived from Tibaldi and Molteni (1990) to have a latitudinal extent reaching the pole. Similarly, our classification of blocking events by flow pattern following the process from Liu and Wang (2025) is a novel application of their work, as no study has yet developed a detection method derived from Tibaldi and Molteni (1990) that incorporates their classification criteria. The outcome of our novel approach is a unique dataset that allows for in-depth analysis of the characteristics of blocking events in the northern hemisphere. While our analysis of most characteristics is not novel (e.g., duration, intensity, maximum spatial area, etc.), the separate analysis of these characteristics by flow type is uncommon among established methods. Further, such analysis has not been performed for blocks classified via the process from Liu and Wang (2025) in published literature.

Chapter 2

Data and Methods

This research utilizes reanalysis data to develop an atmospheric blocking detection algorithm and create a dataset of blocking events in the Northern Hemisphere from 1950 – 2024. The data, detection algorithm, and processes for variable analysis will be provided in this section.

2.1 Data

Geopotential height and specific humidity data are retrieved from ECMWF reanalysis version 5 (ERA5; Hersbach et al., 2020). ERA5 provides global gridded data with a horizontal resolution of $0.25^\circ \times 0.25^\circ$ on 37 pressure levels from 1000 hPa to 1 hPa. This data extends from 1950 – 2024 with a six-hourly resolution, which is resampled to daily. The El Niño Southern Oscillation is defined using the Niño 3.4 SST Index from the Hadley Centre Sea Ice and Sea Surface Temperature version 1.1 data set (HadISST1.1; Rayner et al., 2003), extracted from the NOAA Physical Sciences Laboratory at: <https://psl.noaa.gov/>. The Niño 3.4 SST Index is the area averaged monthly sea surface temperature anomalies over the Niño 3.4 region (5°N - 5°S , 170°W - 120°W) using a reference climatology of 1981 – 2010. The North Atlantic Oscillation is defined using the NAO Index, which is calculated by the Climate Prediction Center (CPC) using Rotated Principal Component Analysis employed by Barnston and Livezey (1987). The NAO Index was extracted from the CPC at: <https://cpc.ncep.noaa.gov/>.

2.2 Blocking Event Dataset

2.2.1 Blocking Detection Algorithm

To produce a dataset of extratropical blocking events in the Northern Hemisphere, a blocking detection algorithm using meridional gradients of 500 hPa geopotential height (Z_{500}) is employed. The algorithm is derived from a procedure developed by Tibaldi and Molteni (1990), is based on Lejenäs and Økland (1983), and adapted by D’Andrea et al. (1998), Scherrer et al. (2006), and Davini et al. (2012). The procedure, hereafter referred to as TM90, quantifies Z_{500} gradients (GHG) at lower and higher latitudes (denoted GHGS and GHGN, respectively) as a function of longitude (λ), using the following definitions:

$$\text{GHGS}(\lambda) = \frac{Z_{500}(\phi_0) - Z_{500}(\phi_S)}{\phi_0 - \phi_S} \quad (2.1)$$

$$\text{GHGN}(\lambda) = \frac{Z_{500}(\phi_N) - Z_{500}(\phi_0)}{\phi_N - \phi_0}, \quad (2.2)$$

where $\phi_N = 80^\circ\text{N} + \Delta$, $\phi_0 = 60^\circ\text{N} + \Delta$, $\phi_S = 40^\circ\text{N} + \Delta$, and $\Delta = -4^\circ, 0^\circ$, or 4° . A given longitude is considered to be blocked at a single instant in time, hereafter referred to as an instantaneous block (IB), if the following conditions are met for at least one Δ within that longitude:

- (1) $\text{GHGS} > 0$
 - (2) $\text{GHGN} < -10 \text{ m deg}^{-1} \text{ lat.}$
- (2.3)

While TM90 is adept in diagnosing the general Z_{500} field of an extratropical anticyclone, it possesses limitations that make it unsuitable for the operational detection of blocking events. Foremost is the lack of consideration for the persistent duration inherent to blocking patterns. Without a temporal constraint, any anticyclone, whether

quasi-stationary or transient, will be designated as an IB. While this is not a concern for data analyzed in a Hovmöller diagram format, a binary dataset (i.e., blocked vs. non-blocked) used for determining long-term blocking frequency will be fundamentally overestimated by a considerable margin. To address this issue, D’Andrea et al. (1998) proposed an additional condition, in which an IB must persist for at least five days to be marked as a blocking episode (BE). This has become a standard metric in subsequent blocking studies. An additional limitation of TM90 is its limited, one-dimensional identification of BEs, as its original function was to analyze blocking frequency on a purely longitudinal basis. It does not account for latitudinal variations in blocking frequency. This has two consequences: (1) blocks at low or high latitude extremes (i.e., with a central anticyclone outside of $60^\circ\text{N} \pm 4^\circ$) are excluded, and (2) the ability to determine the full spatial extent of a block’s central anticyclone does not exist. The absolute geopotential height (AGP) index, proposed by Scherrer et al. (2006) as an adaptation to TM90, addresses this issue by expanding ϕ_0 to include all grid points between 35°N and 75°N . They also reduce the meridional distance between ϕ_0 and both ϕ_S and ϕ_N to 15° (as opposed to 20° in TM90) to prevent ϕ_N from exceeding 90°N . This modification allows the full two-dimensional range of blocking anticyclones to be identified.

As extensively detailed by Pinheiro et al. (2019), the AGP index is one of multiple frequently cited blocking detection methods, each with its own strengths and weaknesses. Among these is the geopotential height anomaly (Z^*) method proposed by Dole and Gordon (1983), which calculates Z_{500} anomalies as departures from the long-term seasonal average, and defines single grid points as blocked if anomalies exceed 100m for at least 10 days. In subsequent studies using this method, both the height and duration thresholds have been changed variably, though the general logic remains consistent. Another approach is the potential vorticity anomaly (PV*) method pro-

posed by Schwierz et al. (2004), which calculates vertically averaged PV anomalies (APV*) in a column from 150-500 hPa, as departures from long-term monthly means. They define regional blocking events as areas of contiguous points that feature APV* values of at most -1.2 PVU for at least 5 days while maintaining a spatial extent of at least 1.8×10^6 km² and a spatial overlap of at least 70% during that time. As opposed to directly evaluating the Z_{500} field to identify persistent anticyclones, the PV* method contends that the negative anomalies indicate anticyclonic circulation at and below the elevated column, while more closely following the shape of the dynamic tropopause. Theoretically, this would provide more direct insight into the influence of stratospheric phenomena on blocking than Z_{500} -based detection methods. This work opts to employ AGP over the PV* method primarily because we focus on tropospheric factors related to blocking, which diminishes the primary advantage of a PV-based approach. Without this advantage, a more straightforward evaluation of the Z_{500} field is more appropriate. Additionally, models such as Energy Exascale Earth System (E3SM; Leung et al., 2020) model lack readily-available PV field data. Furthermore, AGP is preferred over the Z^* method because its blocking detection requirements are more stringent than a simple anomaly threshold and do not rely on the assumption that the Z_{500} field surrounding a potentially blocked ridge represents climatology (Pinheiro et al., 2019).

Before blocking detection is performed, additional alterations are applied to the AGP method. First, the temporal constraint from D’Andrea et al. (1998) is not applied to individual points, but rather to full regional blocking events, which will be outlined later in a subsequent step. For now, the metric is not implemented, meaning that only IBs are identified, not BEs. Second, Scherrer et al. (2006) state that their change in the meridional gradient from 20° to 15° is nominal, and thus we instead opt to initially limit the upper latitudinal bound of ϕ_0 to 70°N , which leaves the original TM90 gradient of 20° unaltered. To avoid cutting off the full spatial extent of high-latitude blocks

by anticyclones that extend beyond the upper bound, we employ a dynamic approach proposed by Burzdak et al. (2026). For $\phi_0 > 70^\circ\text{N}$,

$$\phi_N = \phi_0 + (90^\circ\text{N} - \phi_0) \quad (2.4)$$

$$\phi_S = \phi_0 - (90^\circ\text{N} - \phi_0). \quad (2.5)$$

In doing this, the full range of ϕ_0 becomes 35°N to 90°N without sharply modifying the gradient at a specific latitude.

Finally, a constraint proposed by Davini et al. (2012) to limit the influence of low-latitude blocking (LLB) episodes is added. LLBs are flow patterns above the subtropical eastern Atlantic and Pacific Oceans that resemble strong, persistent ridge events (Santos et al., 2009), which also feature long-lasting anticyclones, but are much more localized than blocks and generally have negligible impacts on Rossby wave circulation. While the AGP index identifies these as blocked points, Davini et al. (2012) suggest that “the detection of LLB events can probably be interpreted as the development of a strong ridge configuration associated with poleward displacement of the subtropical easterlies located south of the blocked area.” Left unfiltered, LLBs drastically overestimate blocking frequency in their associated regions. To address this, the following constraint is added: the meridional gradient of Z_{500} between 15° and 30° south of ϕ_0 must be negative. This guarantees that there are westerly winds south of the point, thereby removing all detected IBs attributed to subtropical easterlies.

2.2.2 Three-Dimensional Mapping

Using this altered AGP index, IBs are identified in the Northern Hemisphere from 1950–2024. The dataset consists of binary tags, with IB points given a value of 1 and all other points given a value of 0. While this is sufficient for characterizing the overall frequency and distribution of blocking over the time period, the goal of this thesis is to identify individual blocking events, which are large and persistent regional patterns that cannot be resolved by analyzing individual grid points. As such, areas of contiguously blocked points must be grouped together in both space and time. To facilitate this task, the TempestExtremes framework is employed (Ullrich et al., 2021). This framework was created to detect, track, and analyze regional atmospheric objects (e.g., extratropical cyclones, atmospheric rivers, monsoonal lows, etc.), with a particular focus on atmospheric blocking. One of its core algorithms, titled StitchBlobs, is specifically utilized. StitchBlobs joins together contiguous areal features, dubbed “blobs,” with matching attributes using a flood fill algorithm. In this case, the matching attribute is the presence of an IB (i.e. points with values of 1 in the binary dataset). This algorithm identifies such features at single timesteps and assigns unique tags to them in the form of (time ID, blob ID). Then, using a forward-backward searching algorithm, overlapping blobs are connected through multiple timesteps and given unique global IDs, creating three-dimensional objects that can merge and split over time. Figure 2.1 illustrates this process. At time index 1, there are two distinct blobs with tags (1, 1) and (1, 2). At time index 2, blob (1, 1) migrates spatially and becomes (2, 1), while at the same time, blob (1, 2) splits into blobs (2, 2) and (2, 3). Then at time index 3, blobs (2, 1) and (2, 2) merge to create blob (3, 1), while blob (2, 3) migrates spatially and becomes (3, 2). Finally at time index 4, blob (3, 1) evolves into blob (4, 1), while blob (3, 2) dissipates. Because every blob was connected to another at

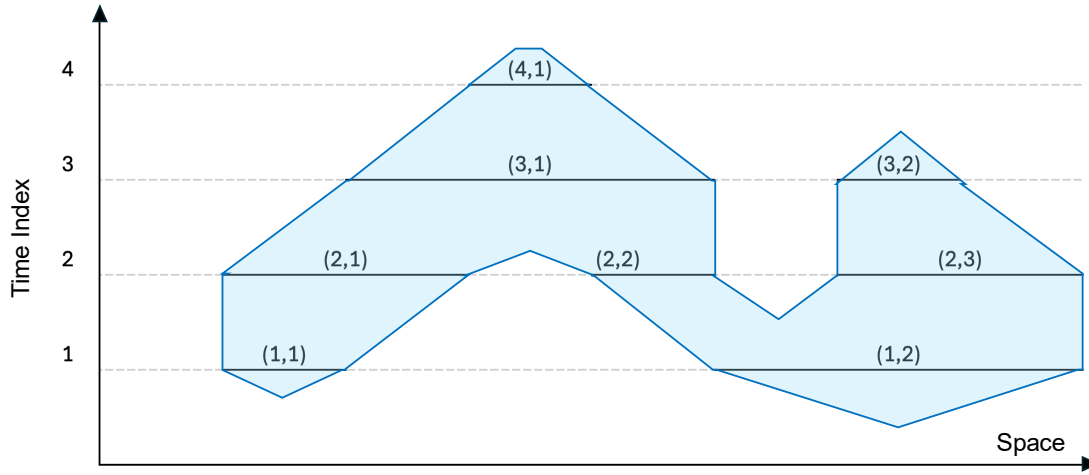


Figure 2.1: A reproduction of Figure 1 from (Ullrich et al., 2021) depicting the forward-backward searching algorithm used by StitchBlobs. The process is simplified to show one spatial dimension and one time dimension, with unique tags in the form (time ID, blob ID).

some point from time indices 1–4, they are all given the same global ID. As a result, every tagged feature shaded in blue is considered to be part of the same 3D object by the algorithm. StitchBlobs provides two additional arguments: (1) a minimum spatial overlap can be defined as a percentage of the area of a blob that connects to a blob in the previous time step. For example, if the minimum is set to 25%, a blob is considered unconnected to a blob in the previous timestep, and therefore a different object, if their overlapping points constitute less than that percentage of its spatial area. (2) A minimum temporal duration can be set (in days).

With this algorithm, full blocking events can now be determined from the binary IB dataset. As mentioned earlier, this is where the minimum duration threshold of 5 days is applied. The reason is that when IBs are forced to persist for multiple time steps, the features identified by the algorithm do not capture the total number of IBs in

the blocked area, because unique tags are assigned to points at single time steps. This limits the size of resulting blocking events while also failing to capture the full range of movement that may occur during the block’s lifetime. In addition to the duration threshold, a minimum overlap of 20% is applied, as well as an added constraint that the maximum spatial area of the block in its lifetime must be within 2–7.5 million km². Both thresholds are defined subjectively through manual examination of individual blocking events to identify when detected blocks became unphysical (e.g., “blocks” that span the entire hemisphere for multiple months).

2.2.3 Flow Pattern Classification

With blocking events identified, one more consideration is added. Following Liu and Wang (2025), we split blocking events into distinct flow patterns: Ridge and dipole blocks, as well as troughing events/cutoff lows. They observed opposite effects on blocking formation and maintenance resulting from the same mid-tropospheric diabatic heating processes, suggesting that separately analyzing flow patterns separately may explain the influence of dynamical factors on blocking with greater accuracy than simply grouping all blocks together. In their paper, blocks are categorized into separate flow patterns using local wave activity (LWA) first described by Huang and Nakamura (2016), which essentially approximates the “waviness” of the atmosphere at a specific location (i.e., the magnitude at which atmospheric circulation has been displaced away from a zonally symmetric reference state). While this was originally quantified using PV contours, Martineau et al. (2017) developed a method that instead utilizes Z_{500} . In his paper, LWA is defined as

$$\text{LWA}(\lambda, \phi_e) = \text{LWA}_A(\lambda, \phi_e) + \text{LWA}_C(\lambda, \phi_e), \quad (2.6)$$

in which LWA consists of the summation of anticyclonic (LWA_A) and cyclonic (LWA_C) components, with λ representing longitude and ϕ_e representing equivalent latitude. Equivalent latitude is defined as the latitude in which the area enclosed between itself and the pole is equal to the same area enclosed by at which a given Z_{500} contour. In effect, this describes the latitude that a Z_{500} contour would have if it were zonally averaged.

As for the components of LWA:

$$\text{LWA}_A(\lambda, \phi_e) = \frac{a}{\cos \phi_e} \int_{z_e \geq 0, \phi \leq \phi_e, \lambda = \text{const}} z_e \cos \phi d\phi, \quad (2.7)$$

and

$$\text{LWA}_C(\lambda, \phi_e) = -\frac{a}{\cos \phi_e} \int_{z_e \leq 0, \phi \geq \phi_e, \lambda = \text{const}} z_e \cos \phi d\phi, \quad (2.8)$$

where a is the Earth's radius, ϕ is latitude, λ is longitude, and

$$z_e = Z_{500} - Z(\phi_e)$$

is the deviation of the height field from the zonally averaged Z_{500} contour at its equivalent latitude. Liu and Wang (2025) suggest that a block's flow pattern can be identified by comparing the magnitude of anticyclonic and cyclonic components of LWA. To do this, they select the date in a block's lifetime in which the maximum LWA is reached. Then, they average LWA_A and LWA_C over all grid points in the block at that time step. If:

$$\text{LWA}_{A,\text{total}} > 10 \text{LWA}_{C,\text{total}}, \quad \text{ridge block} \quad (2.9)$$

$$10 \text{LWA}_{C,\text{total}} > \text{LWA}_{A,\text{total}} > 0.5 \text{LWA}_{C,\text{total}}, \quad \text{dipole block} \quad (2.10)$$

$$0.5 \text{LWA}_{C,\text{total}} > \text{LWA}_{A,\text{total}}, \quad \text{trough event or cutoff low.} \quad (2.11)$$

Conceptually, this means that if the anticyclonic component of LWA in a block is at least an order of magnitude stronger than the cyclonic component (i.e., a single ridge dominates the flow pattern), it is defined as a ridge block. If the anticyclonic component is generally comparable to the cyclonic component (i.e., both an exaggerated ridge and trough are central to the block), it is defined as a dipole block. If the anticyclonic component is less than half of the cyclonic component (i.e., a single trough dominates the flow pattern), it is defined as a trough event or cutoff low. Though sharing characteristics to blocks (i.e., long persistence, quasi-stationarity), trough events and cutoff lows are not usually considered to be blocking events, as they are not ridge-dominated systems (Pinheiro et al., 2019). Therefore, all events defined as such are removed from the dataset.

2.2.4 Block Characterization

With the dataset of blocking events in the Northern Hemisphere from 1950–2024 complete, the characteristics of each blocking event are identified. These include start date, end date, duration (in days), minimum and maximum spatial area (including the days in which these were achieved), and the averaged central coordinate of the blocked area at the start date. LWA and its components (LWA_A and LWA_C) are also recorded, as well as the type of flow pattern. Additionally, following Wiedenmann et al. (2002), the intensity of each block, quantified by the blocking intensity (BI), is calculated as

$$\text{BI} = 100.0 \left[\frac{\text{MZ}}{\text{RC}} - 1.0 \right], \quad (2.12)$$

where MZ is the maximum 500 hPa height achieved at any time step of the block's lifetime and RC is the representative contour defined as:

$$\text{RC} = \frac{1}{2} \left(\frac{Z_u + \text{MZ}}{2} + \frac{Z_d + \text{MZ}}{2} \right), \quad (2.13)$$

where Z_u and Z_d represent the lowest geopotential height values of the trough axis upstream and downstream of MZ at the same latitude and time step, respectively. While the authors do not set a limit on how far Z_u and Z_d can be from MZ, an additional longitudinal constraint is applied such that they must lie within 90°W/E to avoid including minima that may not be part of the blocking pattern. BI ranges from 1 to 10, with blocks classified into three regimes: weak ($\text{BI} < 2.0$), moderate ($2.0 \leq \text{BI} < 4.3$), and strong ($\text{BI} \geq 4.3$). With this, the BI, MZ, coordinates of MZ, and the date of MZ occurrence (designated the date of peak intensity) are recorded.

2.3 Analysis

2.3.1 Blocking Event Subgrouping

Due to the wide seasonal and geographic variability of blocking events in the Northern Hemisphere (Cheung et al., 2013), it is necessary to create subsets in both space and time to eliminate potential influences from disparate environmental attributes (e.g., seasonal variation in the polar jet stream, continental vs. oceanic regimes, etc.). As such, in addition to evaluating the entire Northern Hemisphere over the full year, blocking events are evaluated separately by season and geographical region. The seasonal separations consist of winter (December, January, February; DJF), spring (March, April, May; MAM), summer (June, July, August; JJA), and autumn (September, October, November; SON), as well as extended winter (November–March; NDJFM) in

some cases. Blocking events are split geographically by their average central coordinate, which is the average latitude and longitude of all blocked points on their start date. These separations are illustrated in Figure 2.2. Corresponding with differences in blocking frequency and characteristics between the Atlantic, Pacific, and continental regions (Lejenäs and Økland, 1983; Tibaldi and Molteni, 1990), blocks are split into Euro-Atlantic, North Pacific, Eurasian, and North American domains. To account for more granular environmental variations within each domain (e.g., oceanic/continental vs. coastal regimes; (Kautz et al., 2022)), eight regions are defined.

2.3.2 Trend Analysis

Due to the relatively infrequent occurrence of blocking events in the Northern Hemisphere, temporal trends are evaluated with an annual resolution. Blocking frequency is defined here as the number of blocks that occur throughout the course of a year. Be-

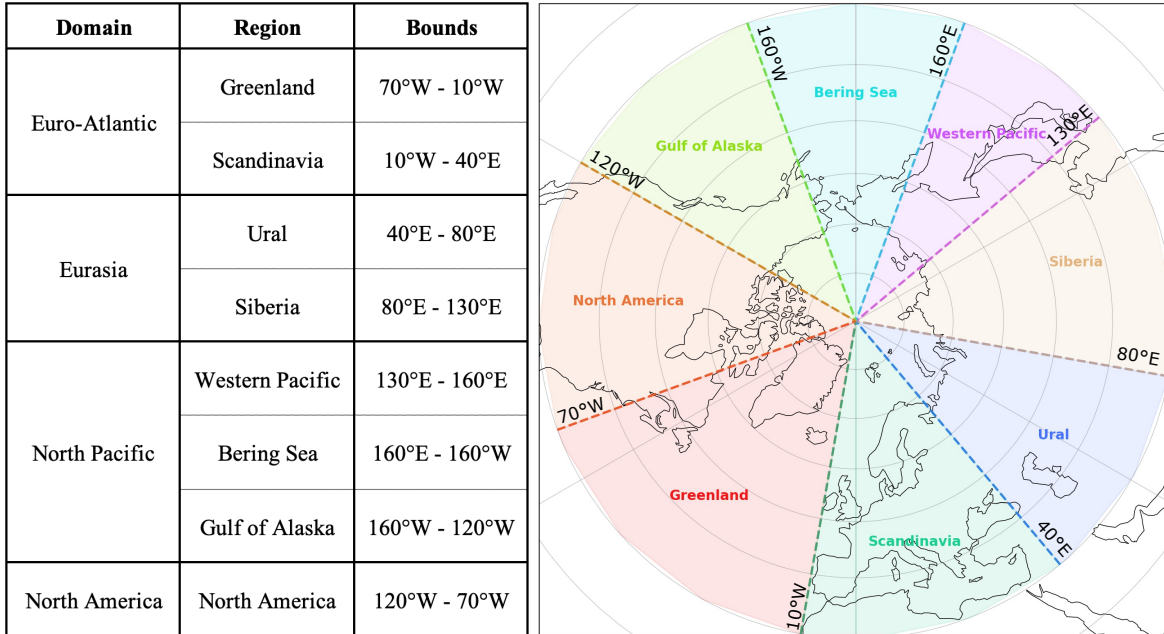


Figure 2.2: (Left) A table of the blocking domains and regions in the Northern Hemisphere. (Right) A map of the regions in the Northern Hemisphere.

cause we are analyzing counts of independent events, Poisson regression is appropriate for modelling the slope of the change in frequency over time (Coxe et al., 2009). This is combined with a Wald test to assess statistical significance (Basu et al., 2020), with a significance threshold of $p < 0.05$. For blocking characteristics, including duration, intensity (blocking index), and maximum spatial area, trends in the annual medians are evaluated to reduce the impact of outliers. For these variables, a Mann-Kendall test is employed to determine if there is a monotonic increase or decrease over time, with a significance threshold of $p < 0.05$. Additionally, a Theil-Sen estimator is used to assess the magnitude of the slope.

2.3.3 Moisture-Induced Diabatic Heating

Latent heating is an important factor in the formation and intensification of Northern Hemisphere blocking events (Crocini-Maspoli and Davies, 2009; Pfahl et al., 2015; Steinfeld et al., 2020; Steinfeld and Pfahl, 2019). An LWA-based framework proposed by Neal et al. (2022) to study the influence of so-called “moisture-induced diabatic heating” on blocking patterns was recently adapted by Liu and Wang (2025) (hereafter referred to as LW25) to examine how the same effects on temperature tendency due to latent heating may affect ridge and dipole blocks differently. Because this work’s detection algorithm employs LW25’s method for classifying blocking flow patterns, intercomparison with their analysis of this variable allows us to test the algorithm’s capability to accurately characterize blocking diversity against an established source, while also providing the opportunity to discover novel insights that were not explored by LW25. As such, LW25’s process for calculating temperature tendency due to latent heating and determining its association with atmospheric blocking diversity is used here. Specifically, their Figure 2 is reproduced. While LWA refers to the analyzed variable as “moisture-induced diabatic heating,” they calculate the term for temperature

tendency due to local latent heating. This term is derived by first referencing the first law of thermodynamics:

$$dU = \delta W + \delta Q, \quad (2.14)$$

with internal energy U , heating Q , and work W :

$$dU = c_v dT \quad (2.15)$$

$$\delta W = -p d\alpha \quad (2.16)$$

$$\delta Q = J dt, \quad (2.17)$$

where c_v is the specific heat of dry air at constant volume, T is temperature, p is pressure, $\alpha = 1/\rho$ is the specific volume (volume per unit mass), and J is diabatic heating. Equation (2.14) is valid for a moving air parcel. However, we follow the process from LW25, which considers only the local temporal evolution at a fixed location. Therefore, we must take the Eulerian time derivative of each term:

$$c_v \frac{\partial T}{\partial t} + p \frac{\partial \alpha}{\partial t} = J. \quad (2.18)$$

Expanding $\partial \alpha$,

$$\partial \alpha = \partial \left(\frac{1}{\rho} \right) = -\frac{1}{\rho^2} \partial \rho. \quad (2.19)$$

Therefore,

$$c_v \frac{\partial T}{\partial t} - \frac{p}{\rho^2} \frac{\partial \rho}{\partial t} = J. \quad (2.20)$$

Then, using the ideal gas law,

$$p = \rho R_d T \quad (2.21)$$

$$\frac{dp}{dt} = R_d T \frac{d\rho}{dt} + R_d \rho \frac{dT}{dt}, \quad (2.22)$$

we can expand the work term:

$$-\frac{p}{\rho^2} \frac{\partial \rho}{\partial t} = -\frac{R_d T}{\rho} \frac{\partial \rho}{\partial t} = -\frac{1}{\rho} \left(\frac{\partial p}{\partial t} - R_d \rho \frac{\partial T}{\partial t} \right) = R_d \frac{\partial T}{\partial t} - \frac{1}{\rho} \frac{\partial p}{\partial t}. \quad (2.23)$$

Therefore, the full equation becomes

$$c_p \frac{\partial T}{\partial t} - \frac{1}{\rho} \frac{\partial p}{\partial t} = J, \quad (2.24)$$

where

$$c_p = c_v + R_d \quad (2.25)$$

is the specific heat of dry air at constant pressure ($1004.5 \text{ J kg}^{-1} \text{ K}^{-1}$). Because we focus just on the temperature tendency, constant pressure is assumed (i.e., $\frac{\partial p}{\partial t} = 0$).

As such, the equation becomes

$$c_p \frac{\partial T}{\partial t} = J. \quad (2.26)$$

To quantify just latent heating, J can be limited to the latent heat release portion of diabatic heating. Using the definition of latent heat:

$$J = \frac{dQ}{dt} = L_v \frac{dm}{dt}, \quad (2.27)$$

where L_v is the latent heat of vaporization ($2.5 \times 10^6 \text{ J kg}^{-1}$) and m is mass. Per unit

mass of moist air, specific humidity is defined as

$$q_v = \frac{m_v}{m_{\text{air}}} \quad (2.28)$$

$$dq_v = \frac{dm_v}{m_{\text{air}}}. \quad (2.29)$$

Condensation produces latent heat, so when latent heat is positive, $dm_v < 0$, and therefore $dq_v < 0$. As such, per unit mass of air,

$$dQ = -L_v \frac{dm_v}{m_{\text{air}}} = -L_v dq_v. \quad (2.30)$$

Taking the partial derivative with respect to time:

$$J = \frac{\partial Q}{\partial t} = -L_v \frac{\partial q_v}{\partial t}. \quad (2.31)$$

This can now be inserted back into (2.26):

$$c_p \left(\frac{\partial T}{\partial t} \right)_{\text{moist}} = -L_v \frac{\partial q_v}{\partial t}. \quad (2.32)$$

Finally, temperature tendency due to latent heating is defined as

$$\left(\frac{\partial T}{\partial t} \right)_{\text{moist}} = -\frac{L_v}{c_p} \frac{\partial q_v}{\partial t} \quad (2.33)$$

This is calculated for every available three-dimensional grid point in the Northern Hemisphere from 1950–2024. To determine the spatial features of $\left(\frac{\partial T}{\partial t} \right)_{\text{moist}}$ around blocking events during their peak intensity, horizontal and vertical centered mean composites are created for both ridge and dipole blocks. Composites are centered around the latitude and longitude at which the maximum 500 hPa height (MZ) occurs on each block's

date of peak intensity. Variables are then averaged together based on their relation to the central coordinate. Horizontally centered composites describe the horizontal structure of $\left(\frac{\partial T}{\partial t}\right)_{\text{moist}}$ and geopotential height at 500 hPa. They encompass $\pm 30^\circ$ longitude and $\pm 20^\circ$ latitude and around the center. Blocks with central coordinates above 70°N are excluded from averaging to ensure that the domain does not extend past 90°N . While this removes the contribution from high-latitude blocking events, they comprise less than 6% of the total dataset, so the bias resulting from their absence is minimal. Vertically centered composites describe the vertical structure of $\left(\frac{\partial T}{\partial t}\right)_{\text{moist}}$ across the blocked region. They encompass $\pm 30^\circ$ longitude and a vertical range of 1000 m to 12000 m. To incorporate the full blocking region, the composites show the meridional average of $\left(\frac{\partial T}{\partial t}\right)_{\text{moist}}$ from $\pm 20^\circ$ latitude with respect to the central coordinate. Height is approximated from pressure coordinates using the standard exponential atmosphere relation:

$$z \approx -H \ln \left(\frac{p}{p_0} \right), \quad (2.34)$$

where z is height in meters, p is pressure in hPa, H is the scale height (7000 m), and p_0 is surface pressure (1000 hPa). Additionally, to determine the temporal evolution of $\left(\frac{\partial T}{\partial t}\right)_{\text{moist}}$ at 500 hPa throughout the lifetime of blocks, Hovmöller diagrams are created for ridge and dipole blocks. Like the vertical centered composites, they cover a range of $\pm 30^\circ$ longitude, though they include a meridional average of just $\pm 10^\circ$ latitude to characterize $\left(\frac{\partial T}{\partial t}\right)_{\text{moist}}$ more closely around the central peaking coordinate. They extend from six days before to six days after the date of peak intensity. To evaluate geographical and seasonal variations that were not addressed by Liu and Wang (2025), additional composites are created separately for each domain and season.

Before analysis, a major caveat in the definition of moisture-induced diabatic heating used in this study must be discussed. Equation (2.33) describes the local Eulerian

temperature tendency due to latent heating, removing the effects of horizontal and vertical moisture advection. At synoptic scales, this advection is highly influential on the total temperature tendency due to latent heating (Kiranmayi and Maloney, 2011; Zhang et al., 2024; Zhu and Hendon, 2014). Therefore, LW25’s employment of the local latent heating term in isolation is not a physically meaningful approach for illustrating the influence of latent heating on the temperature tendency around blocking events. Due to this, the composites described in this section should not be interpreted as valid characterizations of the importance of latent heating for blocking vents. While this is a considerable issue for analyzing the physical drivers behind blocks, latent heating is included in this study not for analysis, but for intercomparison with LW25. As such, consistency with their methods is the primary goal, rather than physical accuracy. Thus, while flawed, the unaltered variable from LW25 is included in this study and referred to as moisture-induced diabatic heating.

2.3.4 Teleconnections

Teleconnection patterns are known to influence global circulation patterns that affect the favorability for blocking formation (Kolstad and O’Reilly, 2024; Wallace and Gutzler, 1981; Wazneh et al., 2021). The intricacies involved in the relationship between these patterns and Northern Hemisphere blocking are an active area of study. Barriopedro and Calvo (2014) (hereafter referred to as BC14) is a good example of this, focusing on the influence of the El Niño Southern Oscillation (ENSO) on the frequency distribution and duration of blocking events. Because they analyze similar blocking characteristics to those studied in this work, intercomparison with BC14 serves as a pertinent test of our algorithm’s ability to accurately represent blocking patterns influenced by prominent teleconnections. It also provides the opportunity expand on their analysis by including the role of blocking diversity. As such, BC14’s process

for compositing blocking event frequency and duration in the Northern Hemisphere between ENSO phases is used here. For the period of 1950–2024, ENSO winters are defined according to the extended winter (NDJFM) average of the Niño-3.4 Index. Extended winters are assigned to the year in which they begin. Consequently, 2024 is not included as it is comprised of only November and December of that year. An extended winter is identified as El Niño when $\text{Niño-3.4} \geq 0.50^\circ\text{C}$, La Niña when $\text{Niño-3.4} \leq -0.50^\circ\text{C}$, and Neutral when $-0.50^\circ\text{C} < \text{Niño-3.4} < 0.50^\circ\text{C}$. All blocking events with start dates outside the extended winter are excluded, with remaining events sorted by ENSO phase. Composites of blocking frequency are created for both El Niño and La Niña winters by calculating the ratio (expressed as a percent) of time steps that each grid point features a block vs. the total number of time steps in the associated phase. Composites of blocking duration are created by identifying the individual blocking events that occurred at each grid point and assigning the mean duration of those blocks to the point. As an expansion of the original study, composites are also created for intensity using the same approach as duration. In addition to the composites for each phase, difference composites are created by subtracting La Niña from El Niño winters. To assess statistical significance, a Monte Carlo test of 1000 samples is performed for all three composites, with significance identified at $p < 0.05$. For the phase composites, random winters with the same sample size as the respective phase are used for the test. To examine the role of blocking diversity, separate composites are also created for ridge and dipole blocks. For analysis of interannual modes of winter-dominant climate variability in other sectors of the Northern Hemisphere, this same process is applied to the NAO (Kolstad and O’Reilly, 2024). Because the NAO does not include a neutral phase, extended winters are identified as positive when the extended winter average (NDJFM) NAO Index is greater than zero, and negative when it is less than zero.

Chapter 3

Results: First-Order Statistics

To evaluate the properties of Northern Hemisphere blocking events identified via our novel blocking detection algorithm, first-order statistics of blocking characteristics and trends over different geographical regions, seasons, and flow patterns are performed. The resulting information is presented in this section.

3.1 Blocking Characteristics

3.1.1 Frequency Distribution

From 1950–2024, 2329 blocking events were identified in the Northern Hemisphere, with an average frequency of around 31 events per year. Blocking frequency over the full year is maximized over the EA and NP domains, with some areas featuring blocking as much as 6–7% of all days in the period (Fig. 3.1a). Seasonally, 676 blocks (29.0%) occur in winter (DJF), 632 blocks (27.1%) in spring (MAM), 520 blocks (22.3%) in summer (JJA), and 501 blocks (21.5%) in autumn (SON) (Table. 3.1). The spatial distribution in winter is similar to that of the full year, with a uniformly higher prevalence of blocking throughout the hemisphere, reaching up to 12% of all winter days over the oceanic domains (i.e., EA and NP). Spring features a shift in distribution away from the lower latitudes and further towards the oceanic domains, though the EA hosts around double the blocking frequency than the NP (12% vs. 6%) during the season.

Blocking Frequency in the Northern Hemisphere from 1950-2024 (35°N-90°N)

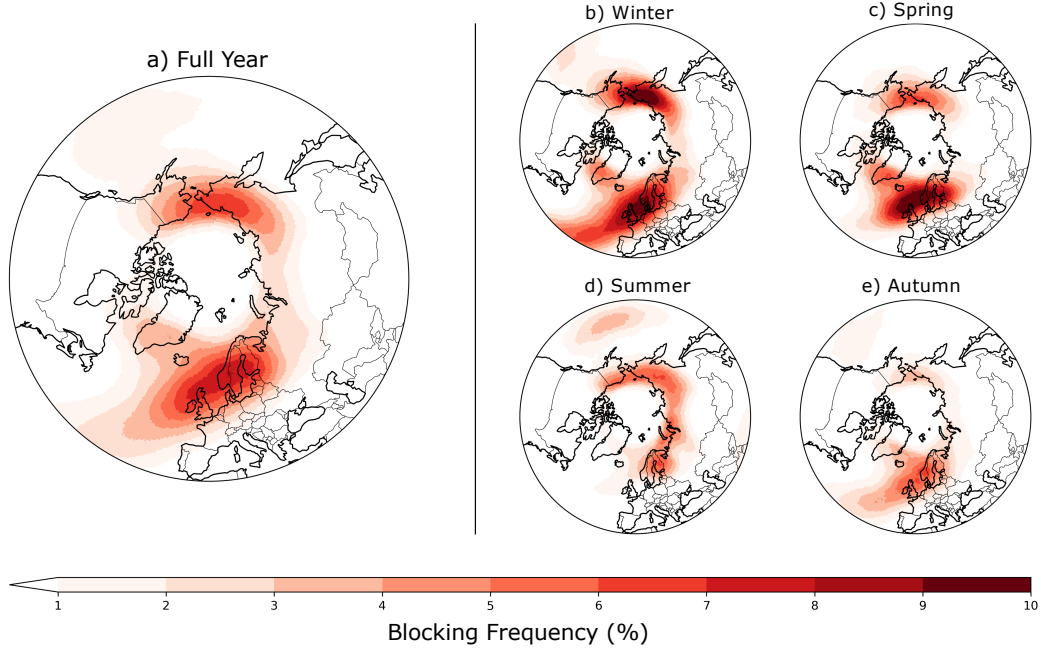


Figure 3.1: Composites of the distribution of blocking frequency for the (a) full year (% of days), (b) winter (DJF), (c) spring (MAM), (d) summer (JJA) and (e) autumn (SON) (% of days in season) in the Northern Hemisphere from 1950–2024.

Summer exhibits a notably different distribution from the rest of the year, with a near absence of blocking over the EA and a central focus over Eurasia and the NP, as well as a small maximum in the lower-latitude Pacific. Autumn has the lowest overall blocking frequency, with events predominantly centered over the EA. A substantial majority of blocking events are located over the oceanic domains, with 1095 blocks (47.0% of all events) in the EA and 812 blocks (34.9% of all events) in the NP. Blocking over the continental domains (i.e., Eurasia and North America) is considerably less common, with just 422 blocks (18.1% of all events) occurring over both domains. The frequency of blocking events over North America, comprising 82 blocks (3.5%), is too low for statistically significant assessment when divided by season or flow pattern ($n < 30$ in both cases), and is consequently excluded from further study.

	N. Hemisphere			Euro-Atlantic			North Pacific			Eurasia		
Season	All	Ridge	Dipole	All	Ridge	Dipole	All	Ridge	Dipole	All	Ridge	Dipole
Annual	2329	1765	564	1095	832	263	812	580	232	340	290	50
DJF	676	550	126	347	260	87	250	218	32	62	59	3
MAM	632	500	132	343	265	78	188	150	38	68	57	11
JJA	520	332	188	126	91	35	232	114	118	154	122	32
SON	501	383	118	279	216	63	142	98	44	56	52	4

Table 3.1: Table of the annual and seasonal number of blocking events in Northern Hemisphere domains, including all, ridge, and dipole blocks.

3.1.2 Blocking Diversity

Of the 2329 blocking events detected between 1950–2024, 1765 (564) were classified as ridge (dipole) blocks (75.8% vs. 24.2%). As the dominant blocking structure, ridge blocks share a similar frequency distribution to the full range of blocking events, though centered further inland (Fig. 3.2). Conversely, dipole blocks are primarily located over the oceanic domains, with 87.8% centered over the EA and NP (Fig. 3.3). As a result, dipole blocks make up 24.0% and 28.6% of blocks over the EA and NP, respectively, while consisting of 16.3% of blocks over the continental domains. Within the oceanic domains, ridge blocks are more prevalent along coastal regions, while dipole blocks are more common further from land (Fig. 3.4). Dipole blocks also tend to reside further equatorward than ridge blocks, with a mean central latitude of 44.9°N versus 57.2°N for ridge blocks. Seasonally, ridge (dipole) blocks make up 81.4% (18.6%) of all winter blocks, 79.1% (20.9%) of spring blocks, 63.8% (32.6%) of summer blocks, and 76.4% (23.6%) of autumn blocks. The more balanced ratio in summer is driven by the NP, which is the only domain that features more dipole than ridge blocks (118 vs. 114) in any season.

Ridge Blocking Frequency in the Northern Hemisphere from 1950-2024 (35°N-90°N)

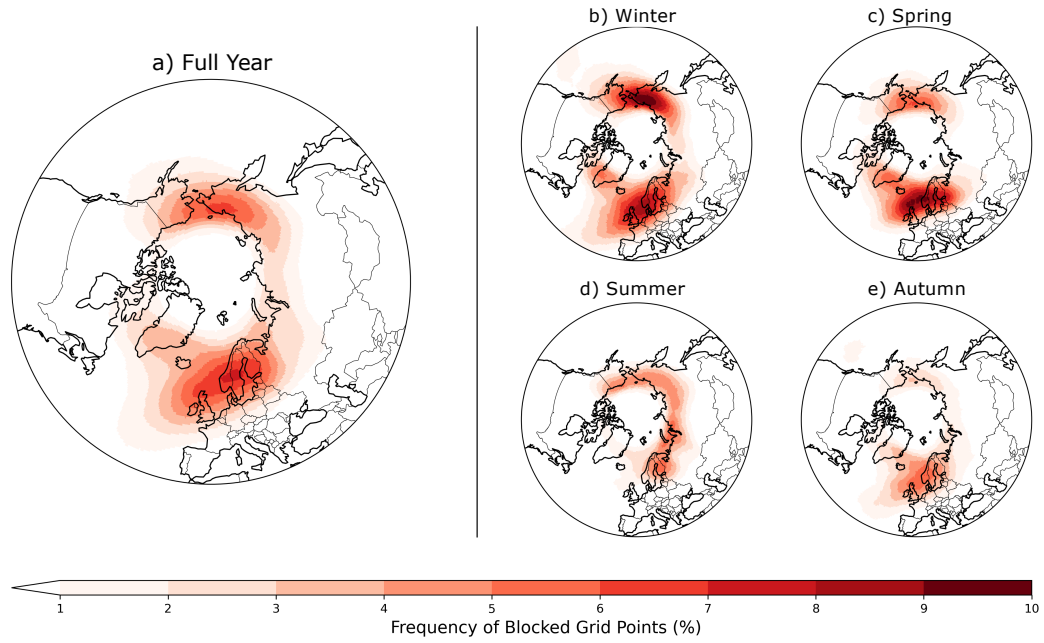


Figure 3.2: As in Figure 3.1 but limited to ridge blocks.

Dipole Blocking Frequency in the Northern Hemisphere from 1950-2024 (35°N-90°N)

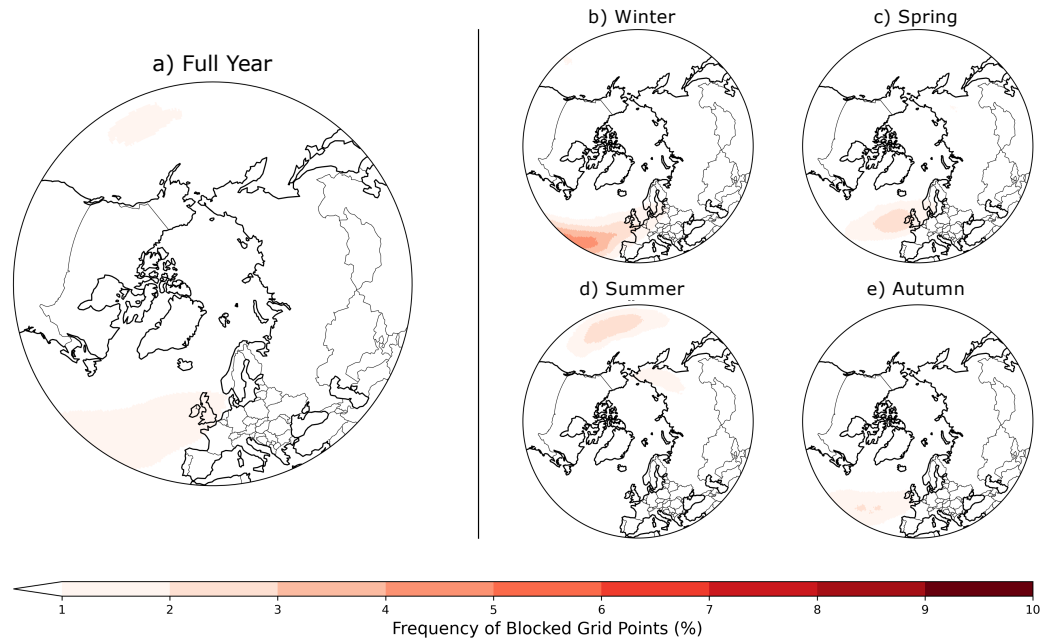


Figure 3.3: As in Figure 3.1 but limited to dipole blocks.

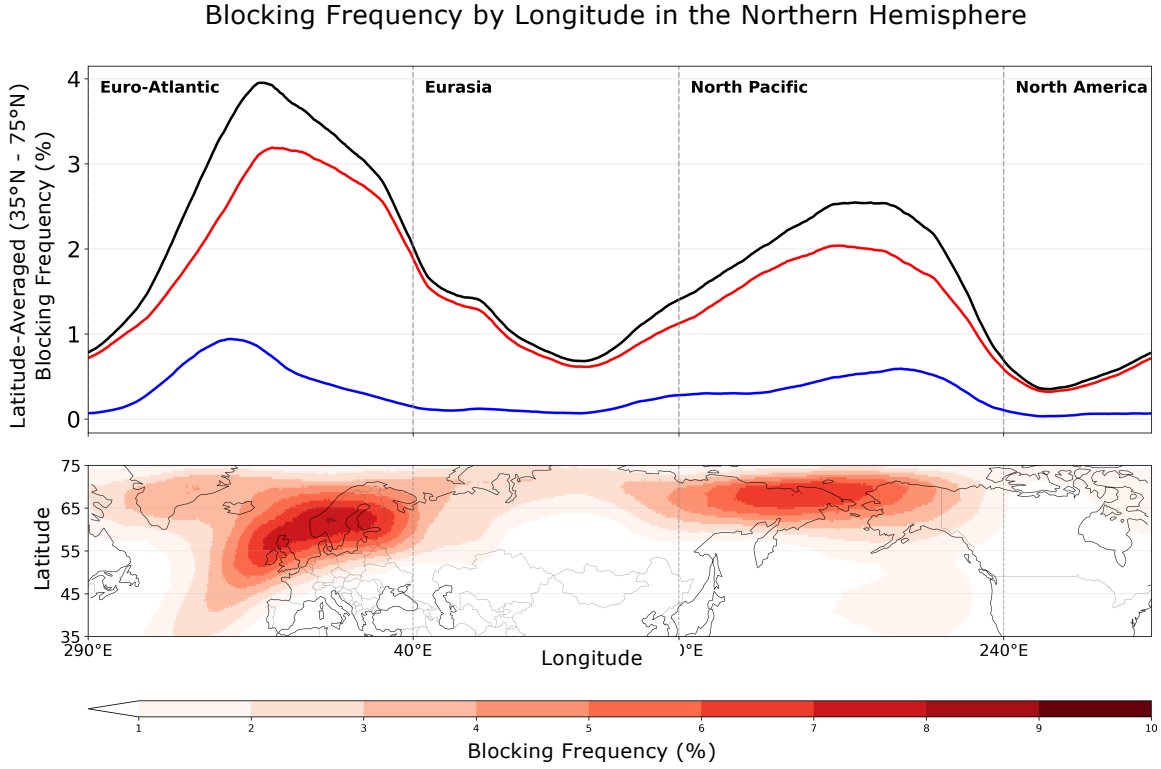


Figure 3.4: (Top) Plot of latitude-averaged (35°N–75°N) blocking frequency (% of days) by longitude for all (black), ridge (red), and dipole (blue) blocks from 1950–2024. (Bottom) Composite of blocking frequency (% of days) in the Northern Hemisphere from 1950–2024.

3.1.3 Duration

The median duration of all Northern Hemisphere blocking events over the full year is 8 days, with an interquartile range (IQR) of 6 to 12 days (Fig. 3.5). Variation between seasons is minimal, with the winter and summer seeing slightly higher medians of 9 days. This increase is driven by the Eurasian domain, which exhibits relatively high seasonal fluctuations compared to the oceanic domains. During the winter and summer, Eurasian blocks have a median duration of 10 days, which falls to 8 days in the spring and autumn. Both the EA and NP see relatively mild variations across the year. However, both domains feature a slight increase in their IQRs in spring and a

slight decrease in fall. Overall, the duration of ridge blocks is consistently higher than that of dipole blocks across all seasons (Fig. 3.6). Ridge blocks have an annual median duration of 9 days and an IQR of 7 to 12 days, while dipole blocks have an annual median duration of 8 days and an IQR of 6 to 10 days. Ridge blocks see minor seasonal variations, with the highest median duration occurring during summer (9 days) and the lowest during autumn (7 days). The increase in duration during the summer aligns with that of Eurasia, where 36.7% of ridge blocks occur during the season. Dipole blocks exhibit even less seasonal variation, with medians ranging from 7 to 8 days.

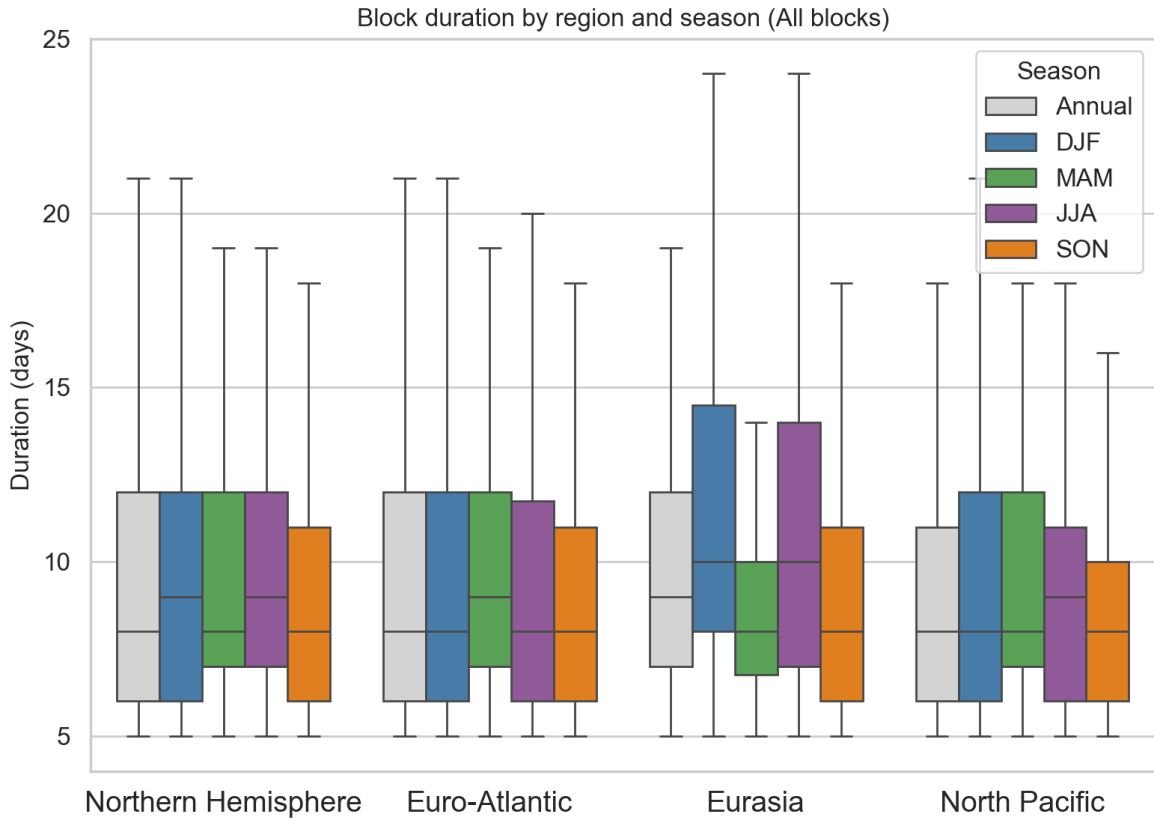


Figure 3.5: Box plot of the annual and seasonal distributions of blocking event duration from 1950–2024 for the Northern Hemisphere, as well as Euro-Atlantic, Eurasia, and North Pacific domains.

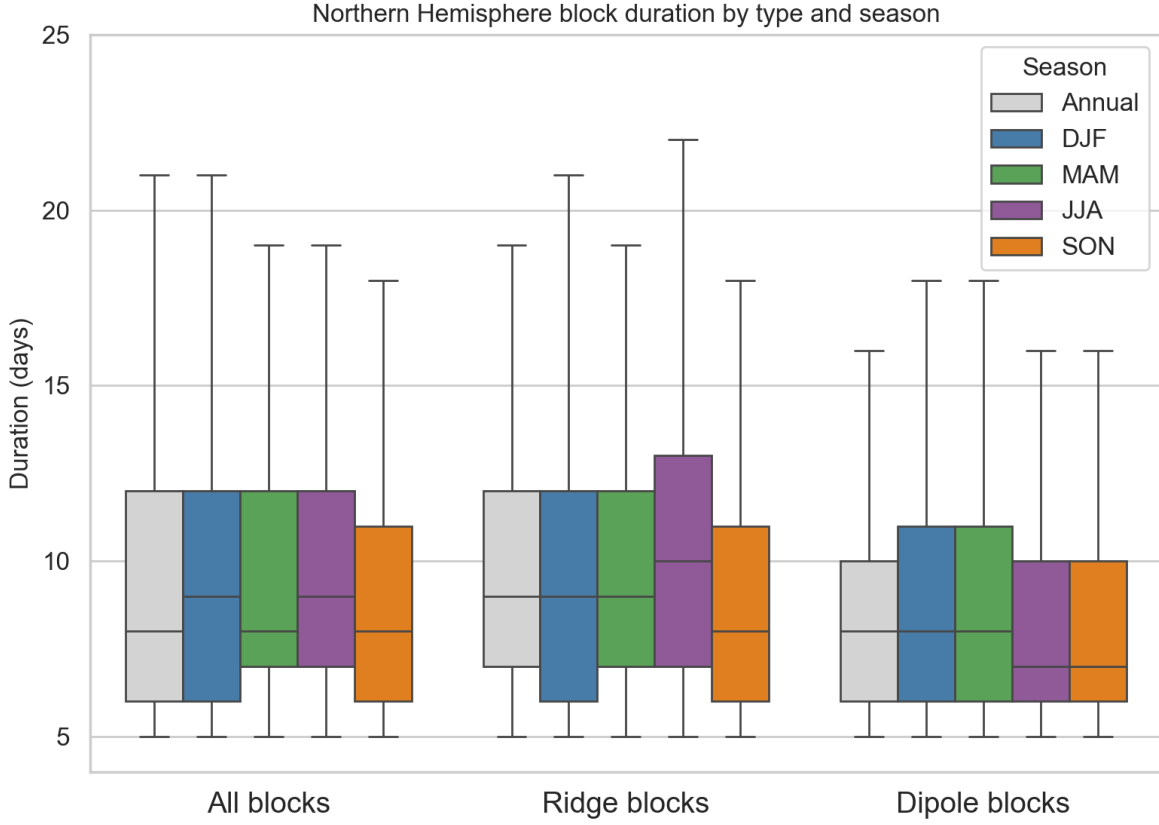


Figure 3.6: Box plot of the annual and seasonal distributions of blocking event duration in the Northern Hemisphere from 1950–2024 for all blocks, ridge blocks, and dipole blocks.

3.1.4 Maximum Spatial Area

The median maximum area of all Northern Hemisphere blocks over the full year is 3.1 million km², with an IQR of 2.4 to 3.10 million km² (Fig. 3.7). A relatively large seasonal variation is evident in all domains, with consistently larger blocking events during winter than any other season. In the EA, NP, and Eurasia, blocks that occur during winter have median maximum areas that are 11.0%, 38.9%, and 10.3% larger than the annual median of their respective domain. The size distribution of Eurasian blocks in winter is statistically larger than that of every other season, with median areas in the spring, summer, and autumn that are within 6.6% of the domain’s annual

median. Eurasia is unique in that blocks that occur during the summer do not have the smallest median area compared to the other seasons, with spring having the smallest instead. Among the oceanic domains, the EA has the largest seasonal variation, with a median maximum area in winter that is 38.0% larger than that of summer blocks. This is partially due to EA blocks that occur during summer having the smallest size of any domain, with a median of 2.5 million km². Winter blocks in the NP have an 18.5% larger median than that of summer blocks. Over the full year, ridge blocks are slightly larger than dipole blocks, with a median maximum area that is 3.4% larger (Fig. 3.8). This is mostly driven by winter ridge blocks, which have a median area 16.6% larger than that of the full year.

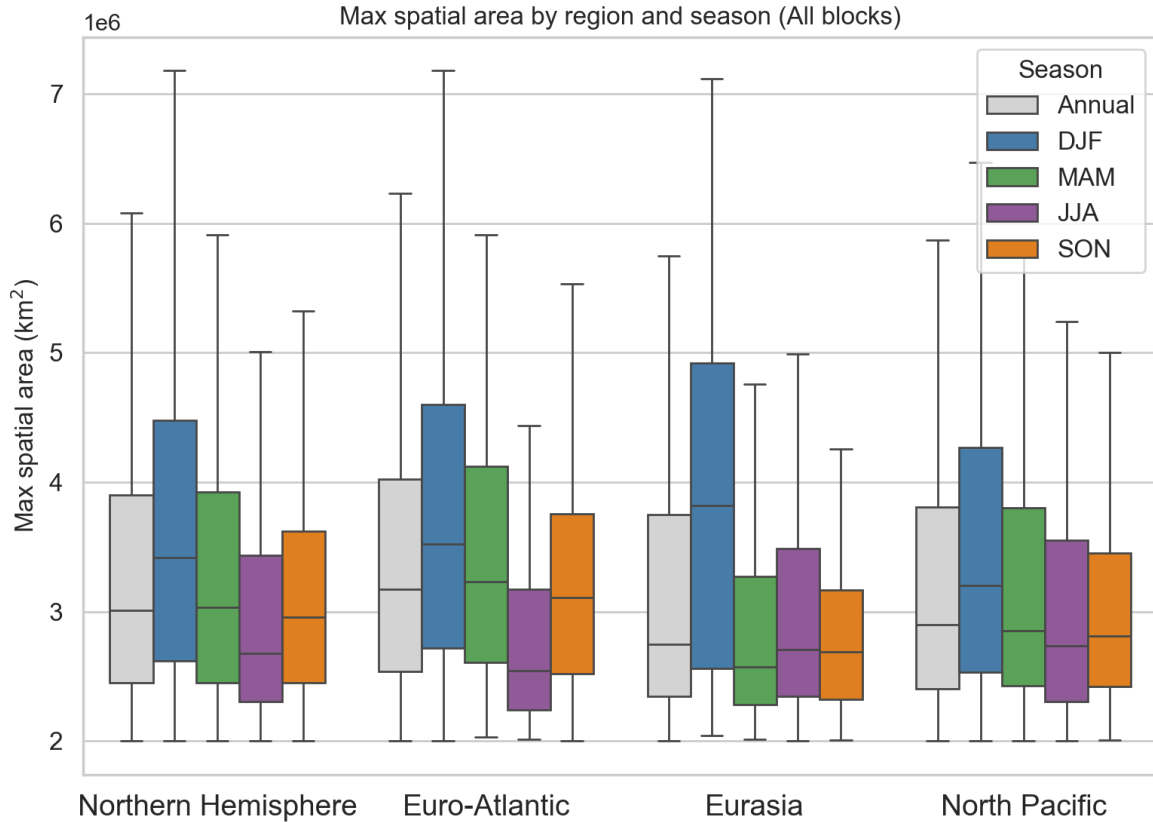


Figure 3.7: As in Figure 3.5 but for the distribution of the maximum area of blocking events.

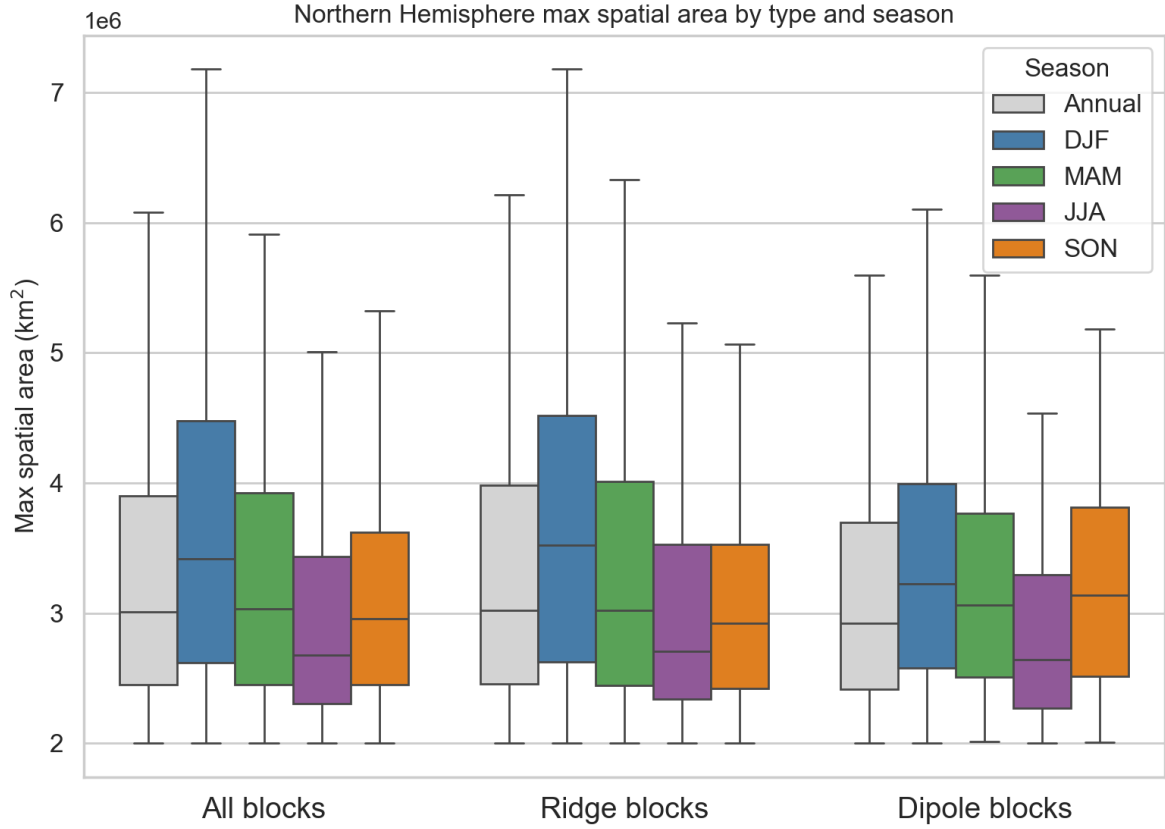


Figure 3.8: As in Figure 3.6 but for the distribution of the maximum area of blocking events.

3.1.5 Intensity

Blocks across the Northern Hemisphere have an annual median intensity of 3.7 and an IQR of 2.8 to 4.7 (Fig. 3.9). Across all domains, blocks that occur during winter are stronger than any other season, with all median winter intensities within the strong range. Conversely, blocks that occur during summer are weaker than those in any other season in every domain. The median intensities of EA, NP, and Eurasian blocks during winter are 70.0%, 102.1%, and 76.6% stronger than those of blocks that occur during summer in their respective domain. EA blocks are the strongest, with an annual median intensity 7.4% stronger than the full hemisphere. Eurasian blocks are

the weakest, with an annual median intensity 12.9% weaker than the full hemisphere. NP blocks have an annual median intensity 3.6% weaker than the full hemisphere. Over both the full year and in every individual season, ridge blocks are stronger than dipole blocks (Fig. 3.10). The median intensity of ridge blocks is 31.3% stronger than that of dipole blocks over the full year, 28.1% stronger in winter, 13.6% stronger in spring, 28.7% stronger in summer, and 39.6% stronger in autumn. Ridge and dipole blocks have similar seasonal variation, with the median intensity of ridge (dipole) blocks that occur during the winter being 75.6% (76.8%) stronger than that of blocks that occur during the summer.

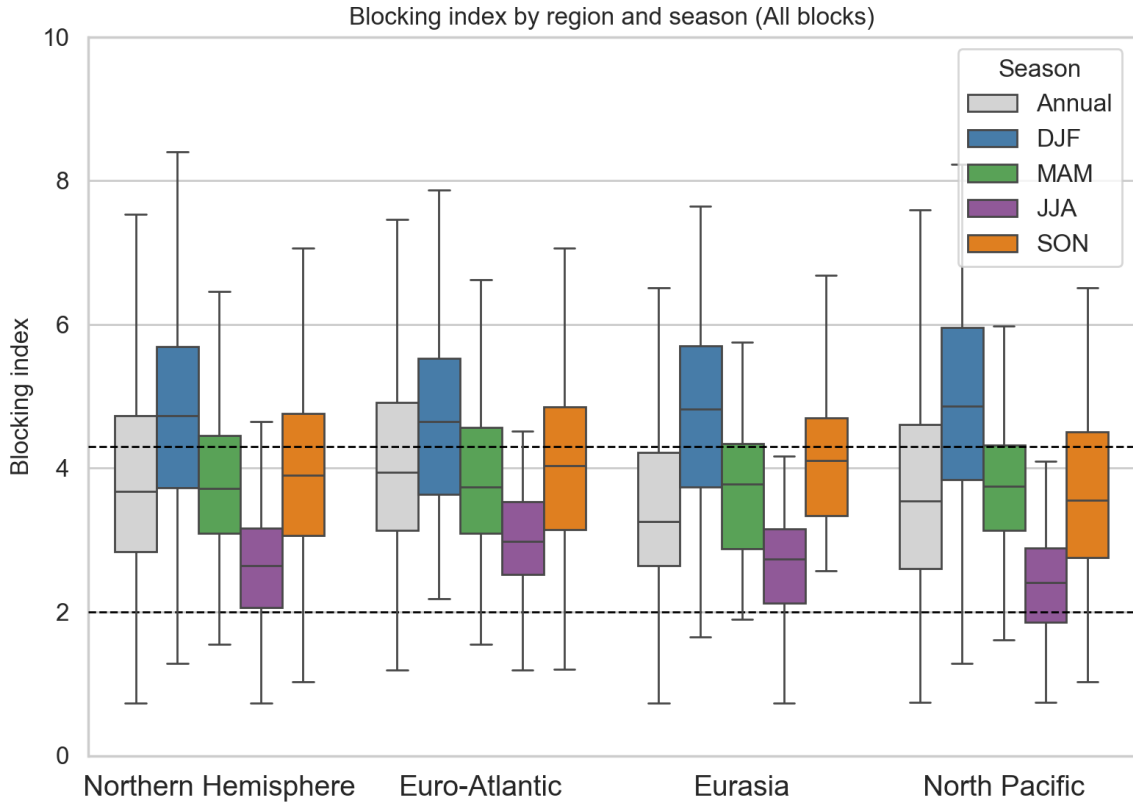


Figure 3.9: As in Figure 3.5 but for the distribution of blocking intensity. Dashed lines indicate intensity thresholds separate weak, moderate, and strong intensity ranges.

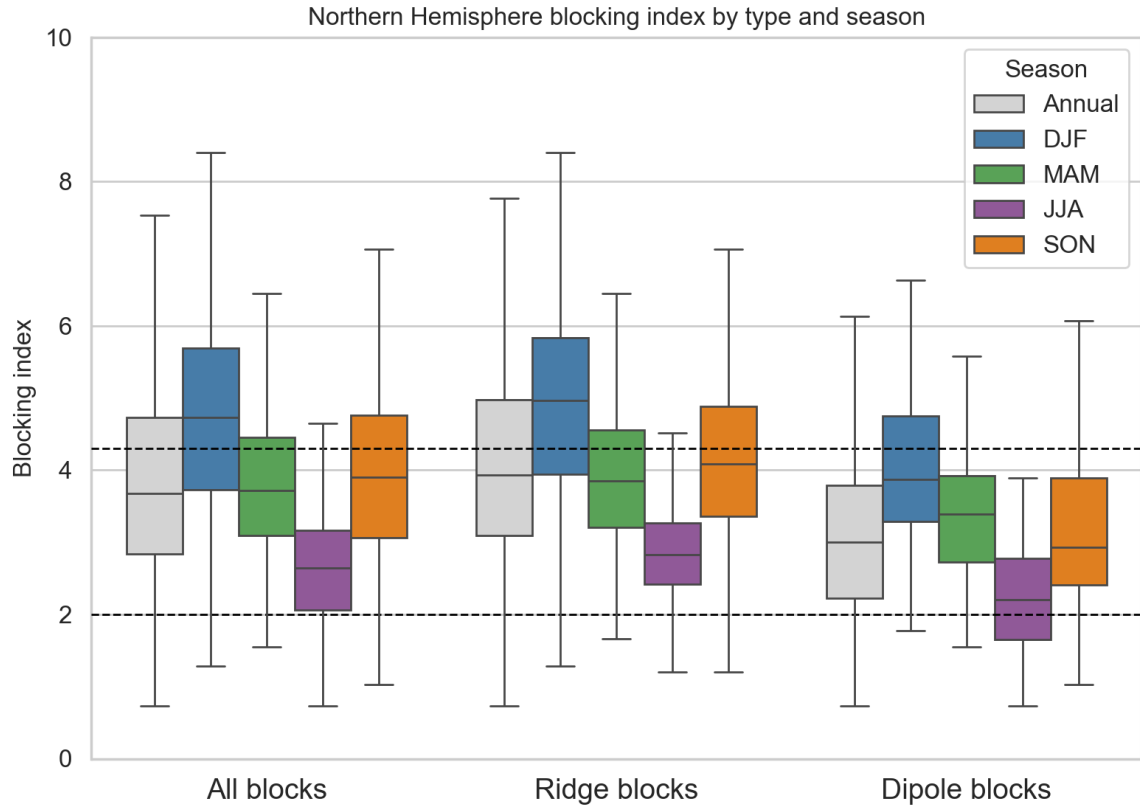


Figure 3.10: As in Figure 3.6 but for the distribution of blocking intensity. Dashed lines indicate intensity thresholds.

3.2 Trends

While basic examination of blocking characteristics is insightful, blocks are subject to strong interannual and interdecadal variability (Martineau et al., 2017) as well as linear trends (Barnes et al., 2014; Croci-Maspoli et al., 2007; Davini et al., 2012; Horton et al., 2015; Wazneh et al., 2021). To fully understand the seasonal and geographical variation of blocking behavior over time, as well as gain insight into the mechanisms responsible for blocking event climatology, this must be considered.

3.2.1 Euro-Atlantic

Across all variables, nearly every trend in the mean seasonal frequency and the medians of the duration, maximum area, and intensity of all, ridge, and dipole EA blocking events fails to meet the 95% statistical significance threshold (Fig. 3.11). However, there is a statistically significant increase in dipole blocks during winter (Fig. 3.11c). There are also positive tendencies in the number of dipole blocks in the spring and autumn, though these are statistically insignificant. The winter trend coincides with weak decreases in the number of ridge blocks during the winter, spring, and autumn over the period (Fig. 3.11b). The total number of blocking events in the EA during these seasons has remained generally consistent, with changes of less than 1% per decade (Fig. 3.11a). This suggests a shift in the ratio of ridge to dipole blocks over time. In fact, of the 444 EA blocking events from 1950–1979, ridge blocks accounted for 79.1%, while of the 443 blocking events from 1995–2024, ridge blocks made up 73.6% of annual events. Seasonally, ridge blocks fell from 82.6% of 138 winter blocks from 1950–1979 to 69.5% of 141 winter blocks from 1995–2024. Likewise, ridge blocks fell from 80.6% of 139 blocks to 77.5% of 142 blocks during spring, as well as from 79.1% of 115 blocks to 72.6% of 113 blocks during autumn. This change is not apparent in the summer, when there is instead an overall decrease in the total number of blocking events during the season. This is driven by a decline in the occurrence dipole blocks, with a less than 1% per decade change in the number of ridge blocks over the period.

The annual median blocking event duration lacks any overall trend in either direction, regardless of the flow pattern (Figs. 3.11d-f). However, there is observable interannual variability, with both ridge and dipole blocks exhibiting periods whose 5-year medians deviate from their overall medians by multiple days in some cases. The annual median of maximum area for all EA blocking events slightly increases over the

Trends in the Euro-Atlantic Domain (1950-2024)

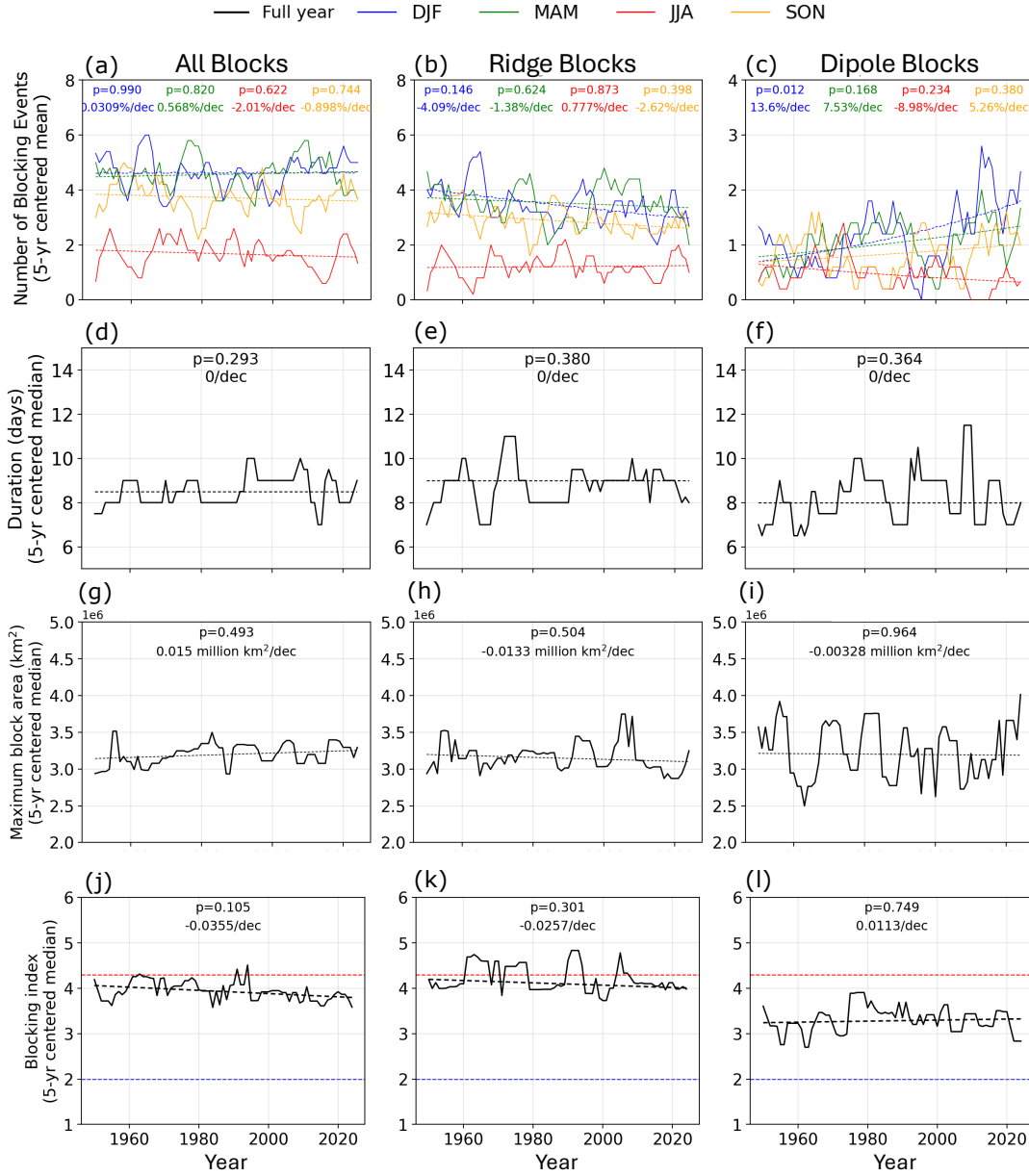


Figure 3.11: Plots of trends in the (a) mean seasonal frequency (number of events per year), (d) median duration, (g) median maximum area, and (j) median blocking index for all blocking events in the Euro-Atlantic domain from 1950–2024, including weak (blue) and strong (red) intensity thresholds. Dashed lines represent trend slope modeled by Poisson Regression. (b, e, h, k) as (a, d, g, j) but for ridge blocks only; (c, f, i, l) as (a, d, g, j) but for dipole blocks only. While 5-year centered means and medians are shown for visual intelligibility, trend slopes and statistical significance have an annual resolution.

period, though not robustly (Fig. 3.11g). Conversely, the medians for both ridge and dipole blocks slightly decrease, though the tendency for dipole blocks is much smaller (Figs. 3.11h-i). The annual median blocking intensity features no robust trends (Figs. 3.11j-l). While the overall annual median for ridge blocks is at the higher end of the moderate intensity range, there are multiple periods in which the 5-year centered median extends into the strong range. While this boundary is arbitrary and does not represent fully distinct types of blocks, it signifies substantial divergence from the usual range of intensity.

3.2.2 Eurasia

Trend in Eurasian blocks are similar to those in the EA (Fig. 3.12). Due to the small sample size of dipole blocks in Eurasia (50 overall), blocks are not split by flow pattern. No analyzed trend exceeds the 95% significance threshold over the period. Seasonally, Eurasia sees a consistent annual mean of around two blocking events per year, while the other seasons feature around one event per year (Fig. 3.12a). The annual median duration shows no trend, remaining at a consistent median of 9 days throughout the period (Fig. 3.12b). The annual median of maximum blocking area decreases slightly, though this is not robust (Fig. 3.12c). While the median annual intensity of Eurasian blocking events has remained generally consistent, there is a noticeable interannual variability present, with the 5-year centered median blocking index varying between approximately 3 and 4 about every 5 to 10 years throughout the period (Fig. 3.12d).

3.2.3 North Pacific

In contrast to the EA and Eurasian sectors, the number of NP blocks exhibits an increasing trend during the summer, with an increase in duration and decrease in

strength annually (Fig. 3.13). Among all NP blocks, there is a statistically significant increase in the annual mean number of blocking events during summer, growing at a rate of 6.72% per decade (Fig. 3.13a). While this is reflected in both ridge and dipole blocks separately, their respective trends are too weak to meet the 95% significance threshold (Figs. 3.13b-c). The annual median duration for all NP blocks has significantly increased by one day over the period (Fig. 3.13d). This is not apparent when separated by flow pattern, with neither ridge nor dipole blocks seeing a trend in either direction (Figs. 3.13e-f). While there are slight negative trends in the annual median maximum blocking area for all flow patterns, none are statistically significant (Figs. 3.13g-i). In contrast, the tendencies in the annual median intensity of NP blocks for all flow patterns are both negative and significantly significant (Figs. 3.13j-l). Over time, the intensity of ridge blocks in the domain decreases from the far high end of the moderate strength range further towards a more intermediate value. At the same

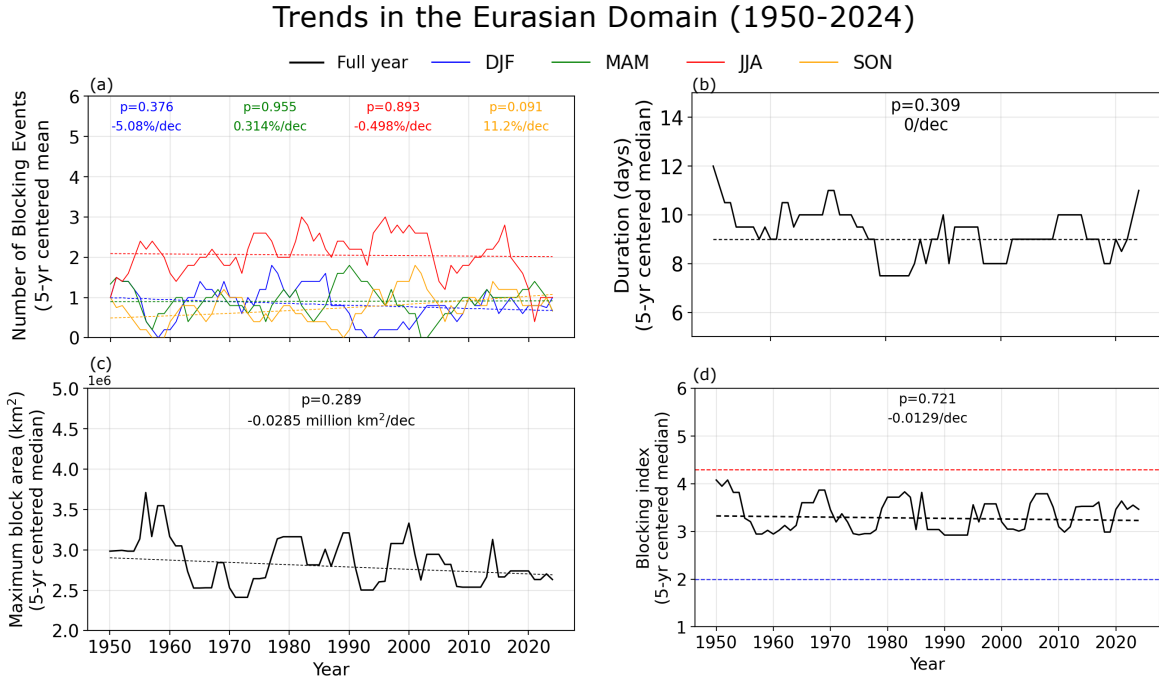


Figure 3.12: As in 3.11 but for the Eurasian domain.

time, dipole intensity decreases at a nearly identical rate, moving towards the low end of the moderate strength range.

Trends in NP blocking events have statistically significant geographic variations within the domain, with sub-divided regions hosting their own statistically significant trends. Of the three regions within the NP, the Bering Sea (BS) and the Gulf of Alaska (GA) exhibit multiple statistically significant tendencies, whereas the Western Pacific does not. While ridge and dipole blocks are presented separately for these regions, low sample sizes ($N < 30$) require caution when interpreting trends. Table 3.2 describes the seasonal and geographic frequencies of blocking events among the NP regions.

	North Pacific			Western Pacific			Bering Sea			Gulf of Alaska		
Season	All	Ridge	Dipole	All	Ridge	Dipole	All	Ridge	Dipole	All	Ridge	Dipole
Annual	812	580	232	141	109	32	326	235	91	345	236	109
DJF	250	218	32	38	37	1	112	99	13	100	82	18
MAM	188	150	38	35	24	11	78	64	14	75	62	13
JJA	232	114	118	48	30	18	81	35	46	103	49	54
SON	142	98	44	20	18	2	55	37	18	67	43	24

Table 3.2: Table of the annual and seasonal number of blocking events in North Pacific domain and associated regions. All, ridge, and dipole blocks are included.

There is a statistically significant increase in the annual mean number of blocking events during spring in the BS region (Fig. 3.14a). This is specifically driven by ridge blocks, which have also seen an increase in annual mean frequency during spring (Fig. 3.14b). While not significant at the 95% threshold, ridge blocks have also seen a weak negative trend in annual mean frequency during winter ($p=0.078$). Dipole blocks have seen an increase in autumn that meets the significance threshold, though this is heavily skewed by an anomalously high number of events in the last five years of the period (Fig. 3.14c). The annual median duration of all blocking events has significantly

Trends in the North Pacific Domain (1950-2024)

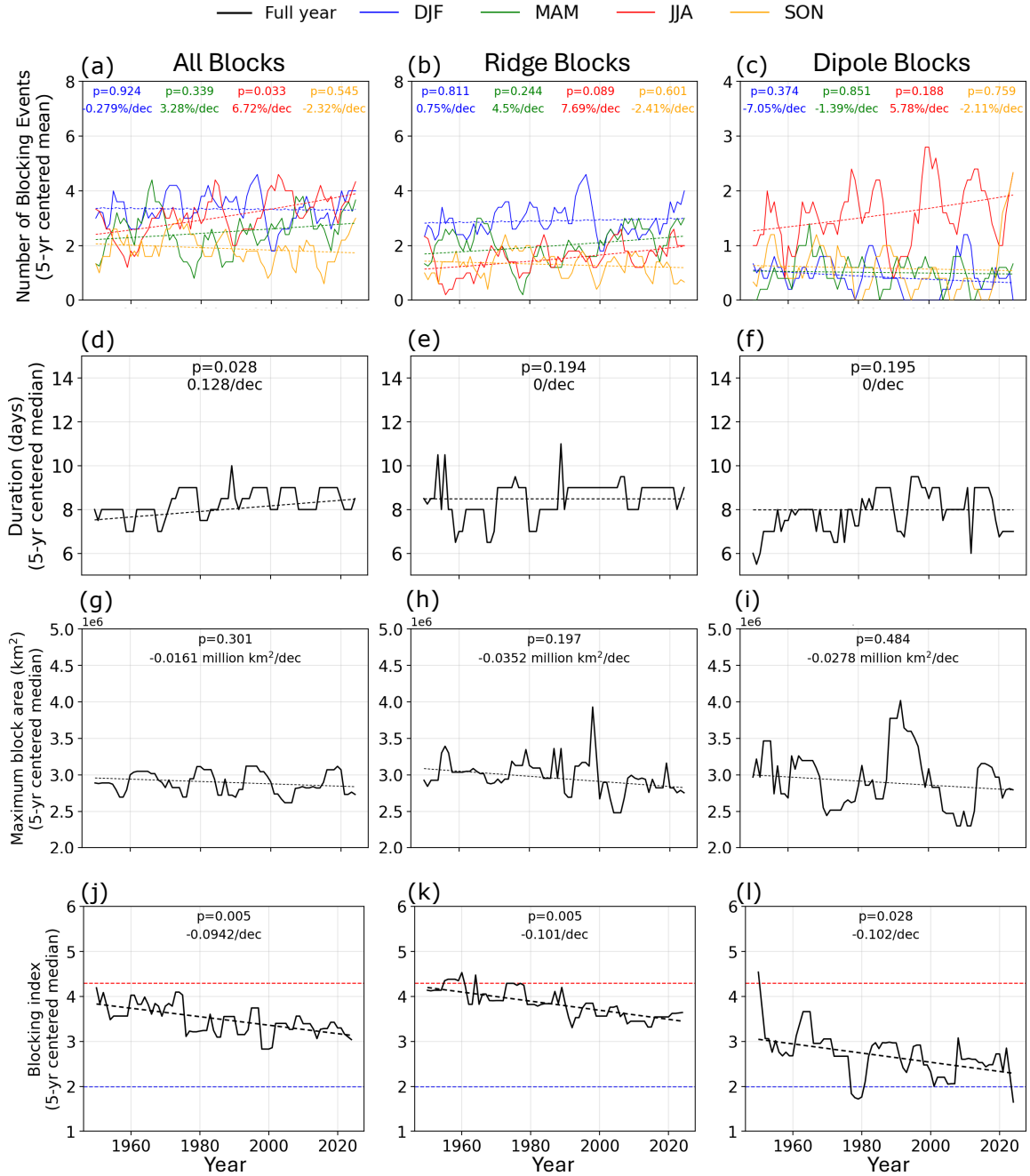


Figure 3.13: As in 3.11 but for the North Pacific domain.

increased in the BS region, which has also been driven by ridge blocks (Figs. 3.14d-e). While there has been a weak increase in the annual median duration of dipole blocks, it is not statistically significant (Fig. 3.14f). The annual median of maximum blocking area features no robust trends (Figs. 3.14g-i). The annual median intensity for all BS blocks decreases throughout the period, though the change is not statistically significant overall (Fig. 3.14j). The decrease is driven by ridge blocks, which do have a significantly negative trend (Fig. 3.14k). Ridge blocks start the period within the strong intensity range, but have moved towards the middle of the moderate range in recent years. Conversely, dipole blocks see a slight positive trend, through this is not robust (Fig. 3.14l).

Among all GA blocks, there is a statistically significant decrease in the annual mean number of blocking events during autumn (Fig. 3.15a). This is led by dipole blocks in the region, which see statistically significant decreases for both autumn and winter (Fig. 3.15c). There are no significant changes in the occurrence ridge blocking (Fig. 3.15b). The annual median duration of all GA blocks significantly increases over the period (Fig. 3.15d). The trend is driven by a robust increase in ridge blocks in the region (Fig. 3.15e). Dipole blocks show no change in duration (Fig. 3.15f). There are no statistically significant changes in the median maximum blocking area, though there is apparent interannual variability (Figs. 3.15g-i). In the case of ridge blocks, there are peaks in maximum area about every twenty years over the period. There is a general decrease in the annual median intensity of GA blocks, though dipoles are the only subset to meet the 95% significance threshold (Figs. 3.15j-l).

Trends in the Bering Sea Region (1950-2024)

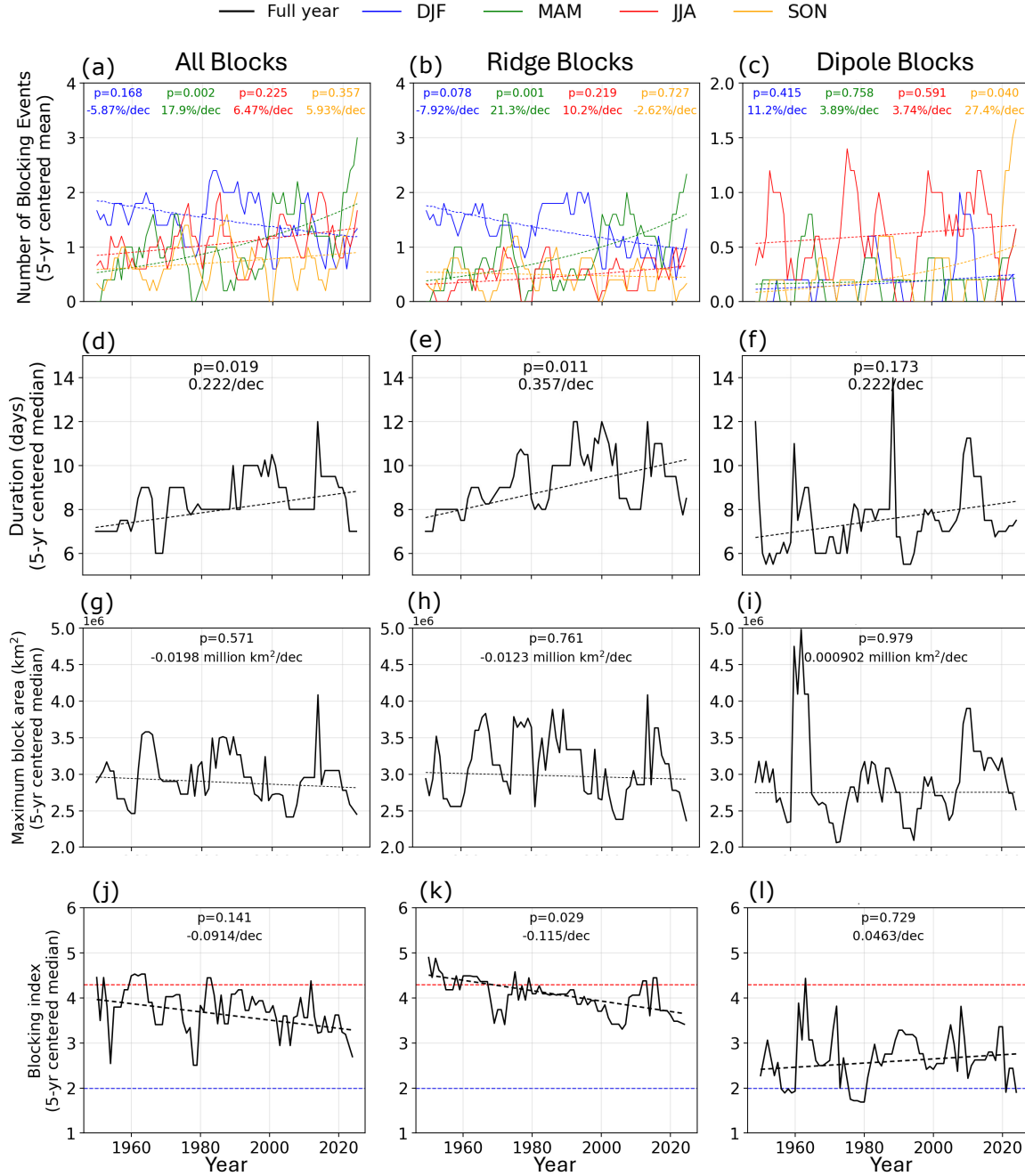


Figure 3.14: As in 3.11 but for the Bering Sea region.

Trends in the Gulf of Alaska Region (1950-2024)

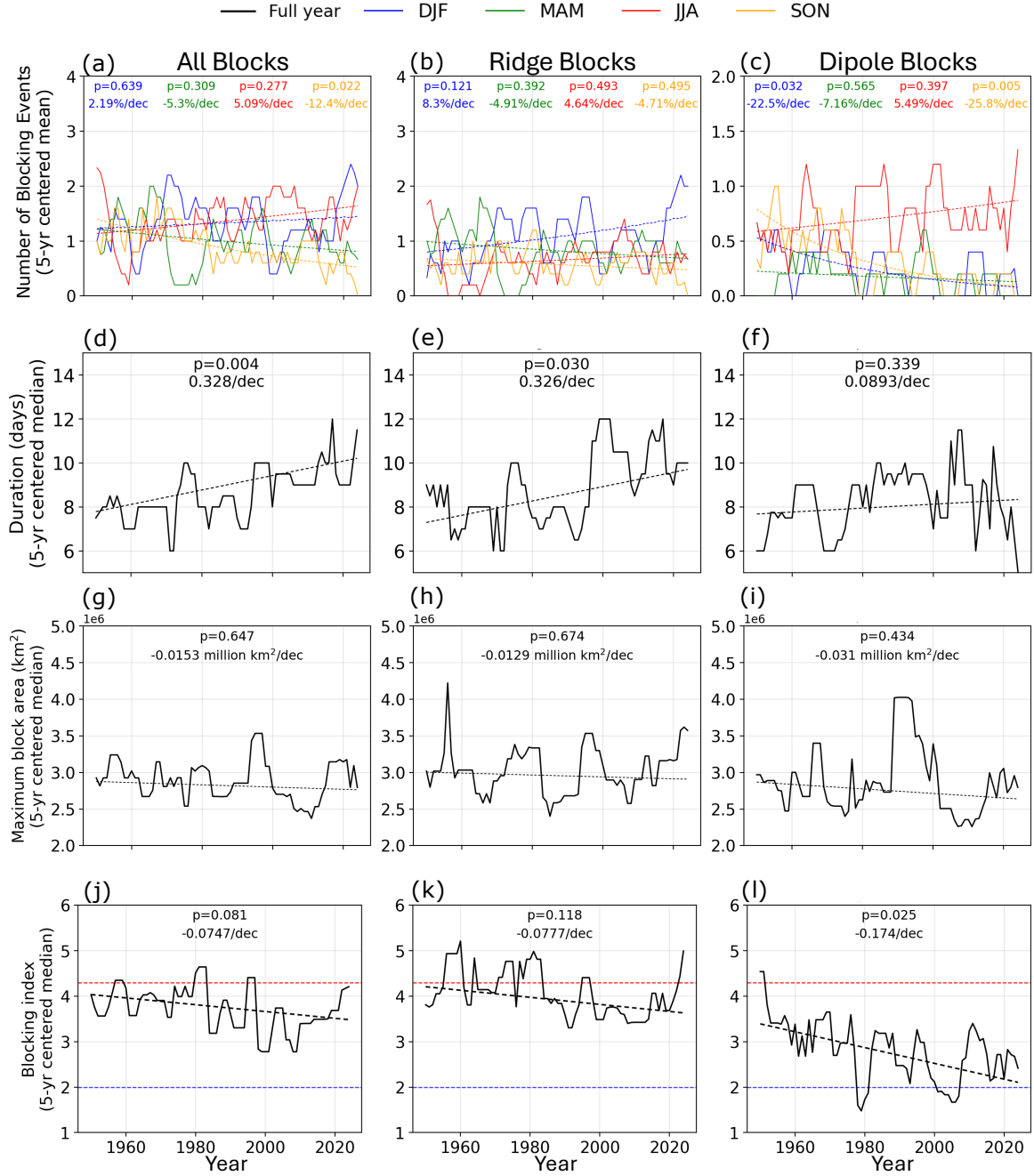


Figure 3.15: As in 3.11 but for the Gulf of Alaska region.

Chapter 4

Results: Blocking Drivers

The blocking event data set created by this work’s novel detection algorithm must be able to veritably represent the physical drivers behind blocking events to be useful for substantive analysis. To assess this ability, results from previous literature are reproduced and expanded upon using the data set. The results of this assessment are presented in this section.

4.1 Moisture-Induced Diabatic Heating

The dynamical factors responsible for blocking formation and maintenance are an active area of study, with the role of diabatic heating at the forefront (Wang et al., 2026). LW25 provides an apt point of comparison for analysis of diabatic heating using this work’s novel dataset. Composited moisture-induced diabatic heating calculated via Equation (2.33) was maximized upstream of ridge blocks at 500 hPa, with heating occurring almost entirely to the west of the block center (Fig. 4.1a). This is consistent vertically, with heating that extends upward to around 6000 m above the surface upstream of the center (Fig. 4.1c). In addition, closer to the surface (<2000 m), slight diabatic cooling occurs near the block center. The Hovmöller diagram for diabatic heating around ridge blocks (Fig. 4.1e) shows diabatic cooling early in the blocking lifespan, with a shift to diabatic heating around the date of peak intensity that endures over multiple days. Dipole blocks see a similar horizontal structure of diabatic

heating at 500 hPa, with heating maximized upstream of the block center, though it is located to the northwest rather than due west (Fig. 4.1b). Diabatic cooling occurs on the opposite side of the block center, centered to the southeast of the block center. Dipoles also feature a similar vertical structure of diabatic heating to ridge blocks, with heating occurring upstream of the block center (Fig. 4.1d). However, heating is stronger at lower levels and extends further in altitude, approaching 7000 m above the surface. The Hovmöller diagram for dipoles (Fig. 4.1f) shows both substantial upstream diabatic heating and cooling in the early stages of the blocking lifespan, with patterns that propagate eastward towards the center over time. In the day leading up to the peak date, cooling occurs to the east and west of the block center, transitioning to heating in the days following the peak.

The spatiotemporal patterns shown here diverge considerably from those observed by LW25. First, the general magnitude of diabatic heating in Figure 4.1 is around an order of magnitude smaller than in LW25. Additionally, they present no diabatic cooling in their composites, while substantial cooling is observed here. The 500 hPa geopotential height contours for both flow patterns do not closely match the published results. While a generally similar ridging pattern appears in both ridge block composites, it is much broader here than in LW25, and there is a height minimum southward of the block center that is not corroborated in their study. There is a greater disagreement between the dipole height contours, with the LW25 composite featuring a distinct ridge to the north and trough to the south of the block center, while the pattern presented here features an S-shape with no closed contours. The horizontal and vertical structures of diabatic heating around ridge blocks are comparable (neglecting magnitude), though the temporal evolution is reversed, with heating early in the blocking lifetime that weakens after the peak date. The diabatic heating structures around dipole blocks vary substantially. LW25 shows a heating maximum south of the block

Spatiotemporal Features of Moisture-Induced Diabatic Heating

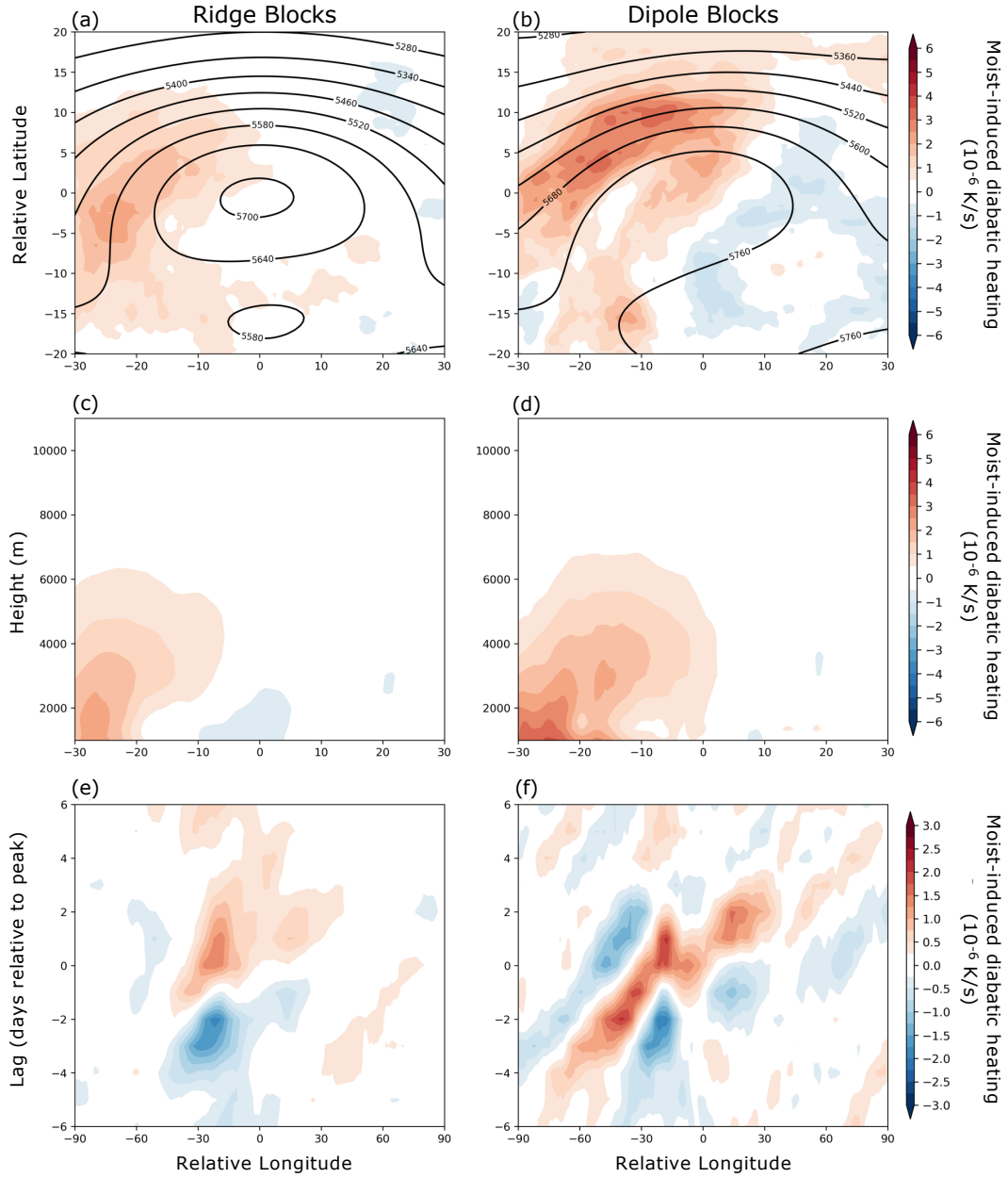


Figure 4.1: Composites of the horizontal and vertical structure of moisture-induced diabatic heating around all ridge (a, c) and dipole (b, d) blocks in the Northern Hemisphere from 1950–2024. Shaded contours indicate moisture-induced diabatic heating, and line contours indicate 500 hPa geopotential height. Panels (e, f) are Hovmöller diagrams of moisture-induced diabatic heating of composited (e) ridge and (f) dipole blocks. Day 0 is the date of maximum blocking intensity.

center, near the geopotential height minimum, which contrasts with the pattern seen here. Vertically, while they observe similar upstream diabatic heating, there is also a heating maximum near the surface adjacent to the block center, as well as an additional downstream plume of heating, neither of which are seen here. Their Hovmöller diagram for dipole blocks suggests a similar eastward propagation of upstream diabatic heating in the leading up to the peak date, though the pattern is disjointed.

In general, the horizontal and vertical structures of diabatic heating around ridge blocks are consistent between winter (Figs. 4.2a-b and 4.3a-b), spring (Figs. 4.2c-d and 4.3c-d), and autumn (Figs. 4.2e-f and 4.3e-f), although upstream heating in autumn is much more extensive than the rest of the year. The temporal evolutions of diabatic heating shown by the Hovmöller diagrams for winter, spring, and autumn ridge blocks (Figs. 4.4a, c, g) are also generally consistent, with the transition from early-stage cooling to later warming occurring in all seasons. However, winter and autumn blocks appear to exhibit eastward propagation of these features, while spring blocks see more zonal stationarity. Summer ridge blocks experience a sporadic horizontal diabatic heating structure, though upstream heating remains the dominant feature (Fig. 4.2e). Vertically, upstream diabatic heating occurs aloft, with cooling near the surface (i.e., 1000–2000 m), an orientation not seen in any other season (Fig. 4.3e). The Hovmöller diagram for summer ridge blocks (Fig. 4.4e) is also sporadic, though the same temporal evolution seen in other seasons is identifiable.

The horizontal structure of diabatic heating at 500 hPa around dipole blocks in winter, spring, and autumn (Figs. 4.2b, d, h) share a similar pattern to that of the full year. Vertically, winter and autumn (Figs. 4.3b, d) dipoles reflect the full-year pattern, though at a larger magnitude. This is especially true for autumn blocks, which exhibit strong upstream heating extending to nearly 8000 m above the surface. Spring and summer dipoles see diabatic heating and cooling both upstream and downstream at

lower levels, though the upstream structures are much stronger (Figs. 4.3d, f) . The Hovmöller diagrams for dipole blocks across all seasons show eastward propagation of diabatic heating and cooling patterns over time (Figs. 4.4b, d, f, h).

Due to the low occurrence of dipole blocks over Eurasia, composites are not analyzed for the domain. Ridge and dipole blocks over the EA possess comparable horizontal diabatic heating structures at 500 hPa, which also correspond to the full hemisphere (Figs. 4.5a-b). This is also the case for the vertical structure of upstream diabatic heating, though dipole blocks exhibit a large plume of diabatic cooling downstream of the block center, which is not reflected by ridge blocks (Fig. 4.6a-b). The Hovmöller diagrams for both EA ridge and dipole blocks are analogous to those of the full hemisphere (Figs. 4.7a-b). Over the NP, the horizontal structure of diabatic heating around ridge blocks features upstream diabatic heating. The maximized area is almost entirely oriented to the southwest of the block center (Fig. 4.5c). Vertically, while there are regions of diabatic heating upstream and cooling downstream of the center, ridge blocks are weak overall (Fig. 4.6c). The Hovmöller diagram for NP ridge blocks shows a similar evolution to other regions, though weaker overall (Fig. 4.7c). The horizontal structure of diabatic heating around NP dipole blocks diverges from both the EA and full hemisphere, with substantial diabatic heating very close to the block center in addition to heating north of the center, as well as upstream (Fig. 4.5d). The vertical structure is also unique, with expansive diabatic heating extending upstream and downstream of the block center, and reaching nearly 7000 m above the surface (Fig. 4.6d). While sporadic, the common temporal evolution of dipole blocks featuring eastward propagation of both diabatic heating and cooling is discernible in the Hovmöller diagram for NP dipole blocks (Fig. 4.7d).

Seasonal Horizontal Structures of Moisture-Induced Diabatic Heating

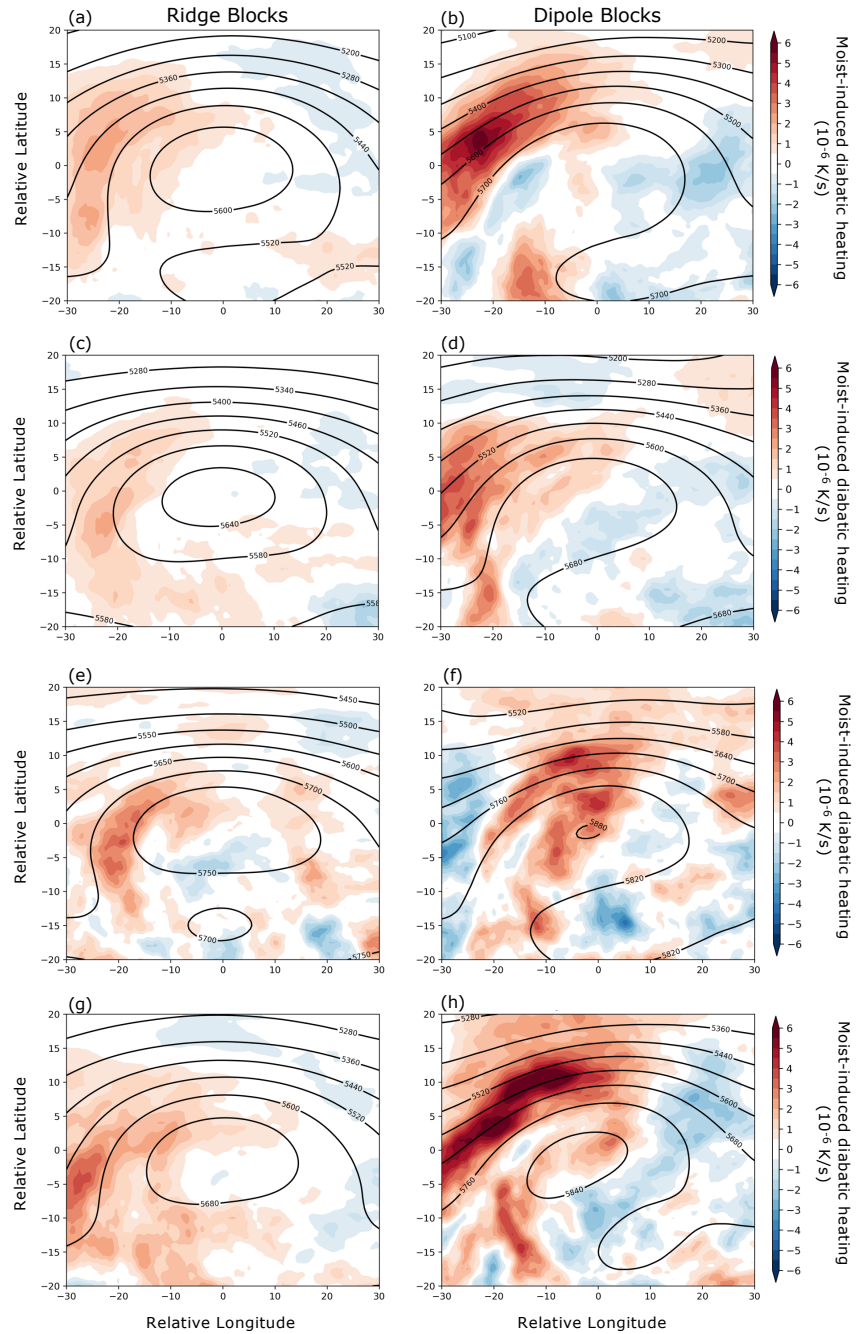


Figure 4.2: Composites of the horizontal structure of moisture-induced diabatic heating around ridge and dipole blocks in the Northern Hemisphere during winter (a, b), spring (c, d), summer (e, f), and autumn (g, h) from 1950–2024. Shaded contours indicate moisture-induced diabatic heating, and line contours indicate 500 hPa geopotential height.

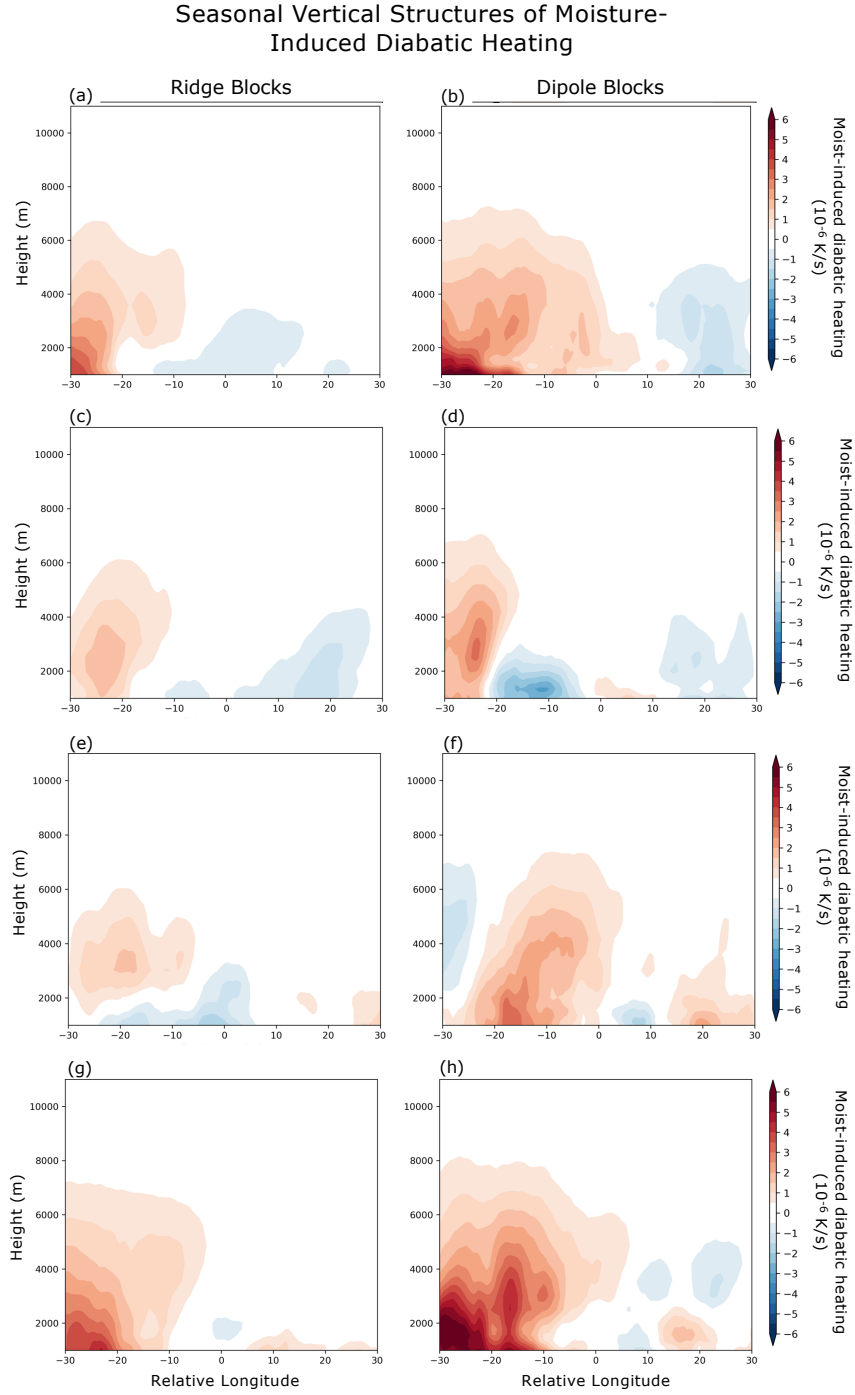


Figure 4.3: Composites of the vertical structure of moisture-induced diabatic heating around ridge and dipole blocks in the Northern Hemisphere during winter (a, b), spring (c, d), summer (e, f), and autumn (g, h) from 1950–2024.

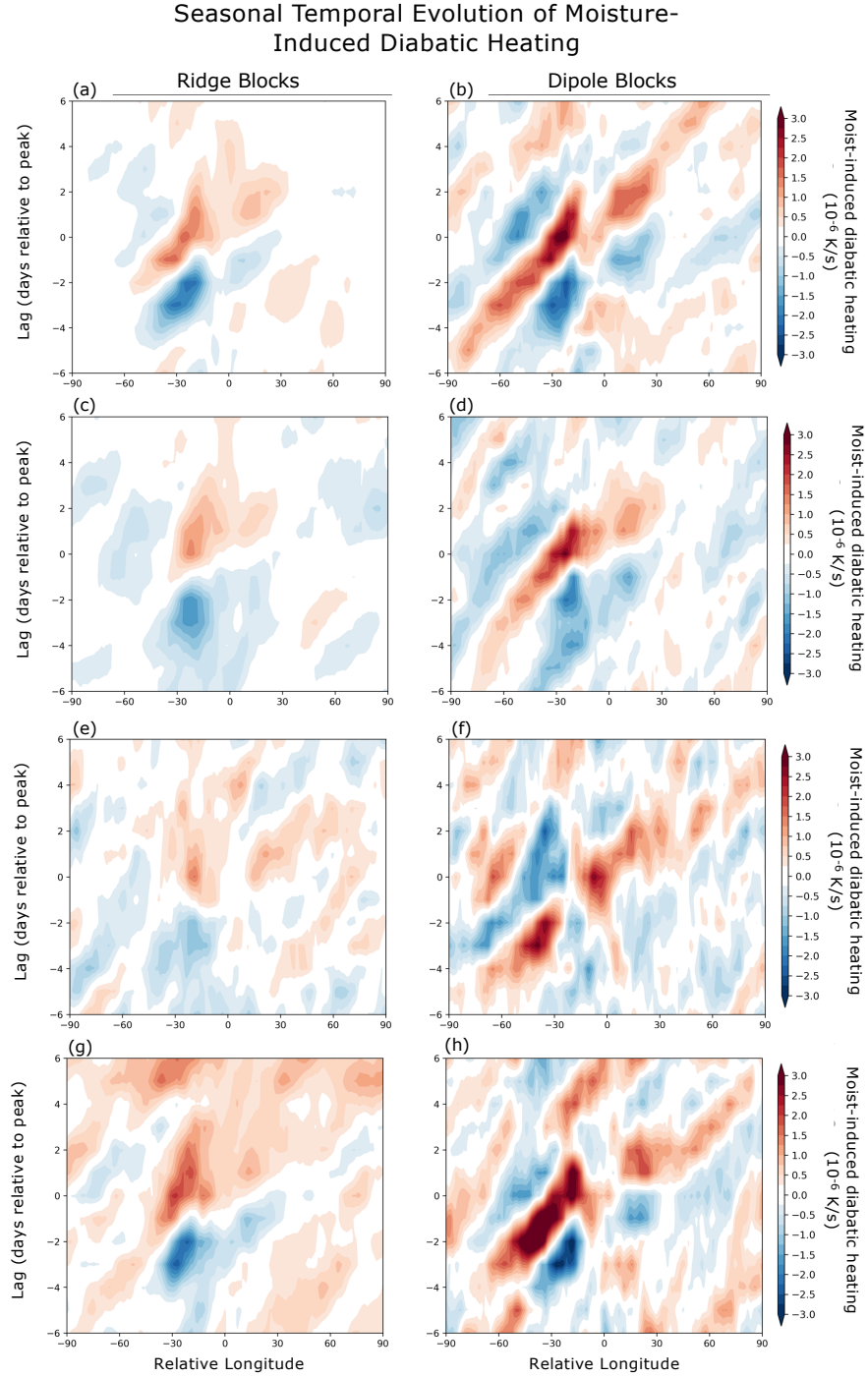


Figure 4.4: Hovmöller diagrams of moisture-induced diabatic heating of composited ridge and dipole blocks during winter (a, b), spring (c, d), summer (e, f), and autumn (g, h) from 1950–2024. Day 0 is the peak date of maximum blocking intensity.

Horizontal Structures of Moisture-Induced Diabatic Heating in the Euro-Atlantic and North Pacific Domains

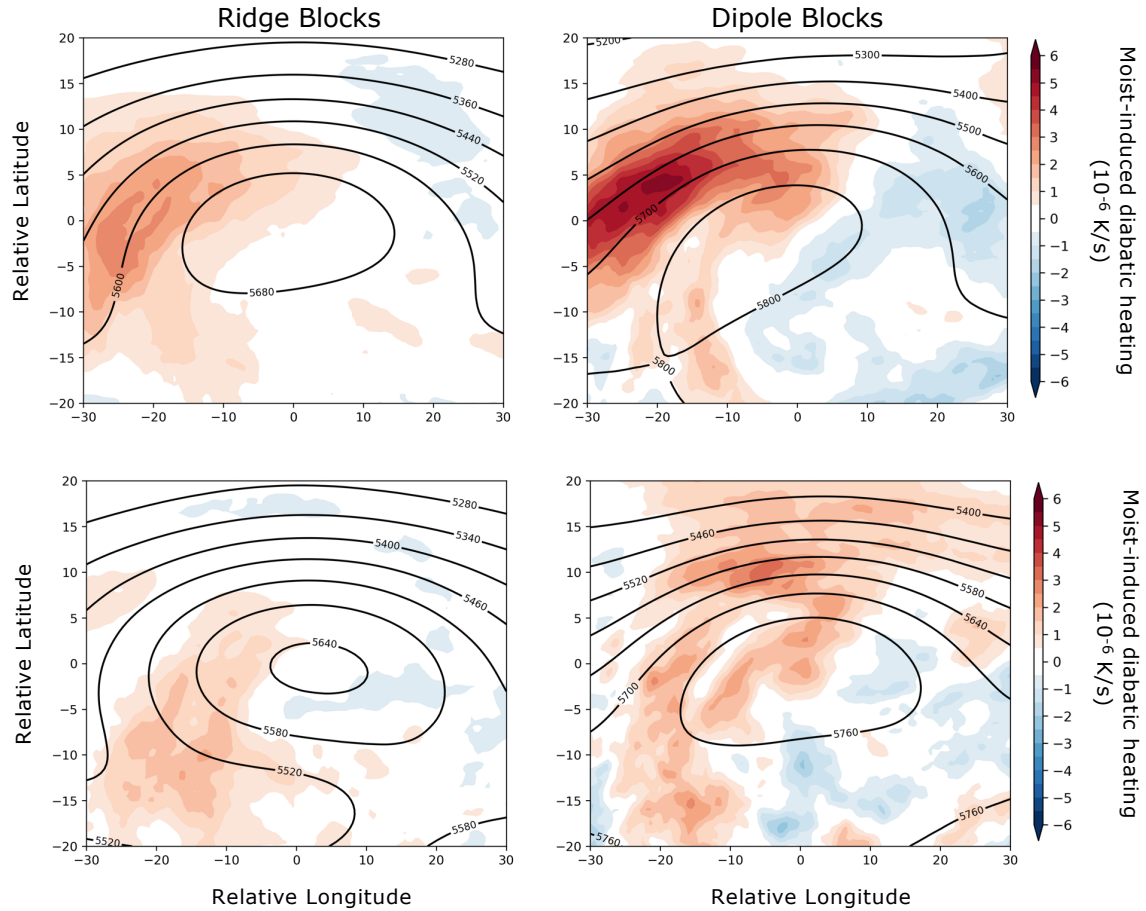


Figure 4.5: Composites of the horizontal structure of moisture-induced diabatic heating around ridge and dipole blocks over the Euro-Atlantic (a, b) and North Pacific (c, d) domains from 1950–2024. Shaded contours indicate moisture-induced diabatic heating, and line contours indicate 500 hPa geopotential height.

Vertical Structures of Moisture-Induced Diabatic Heating in the Euro-Atlantic and North Pacific Domains

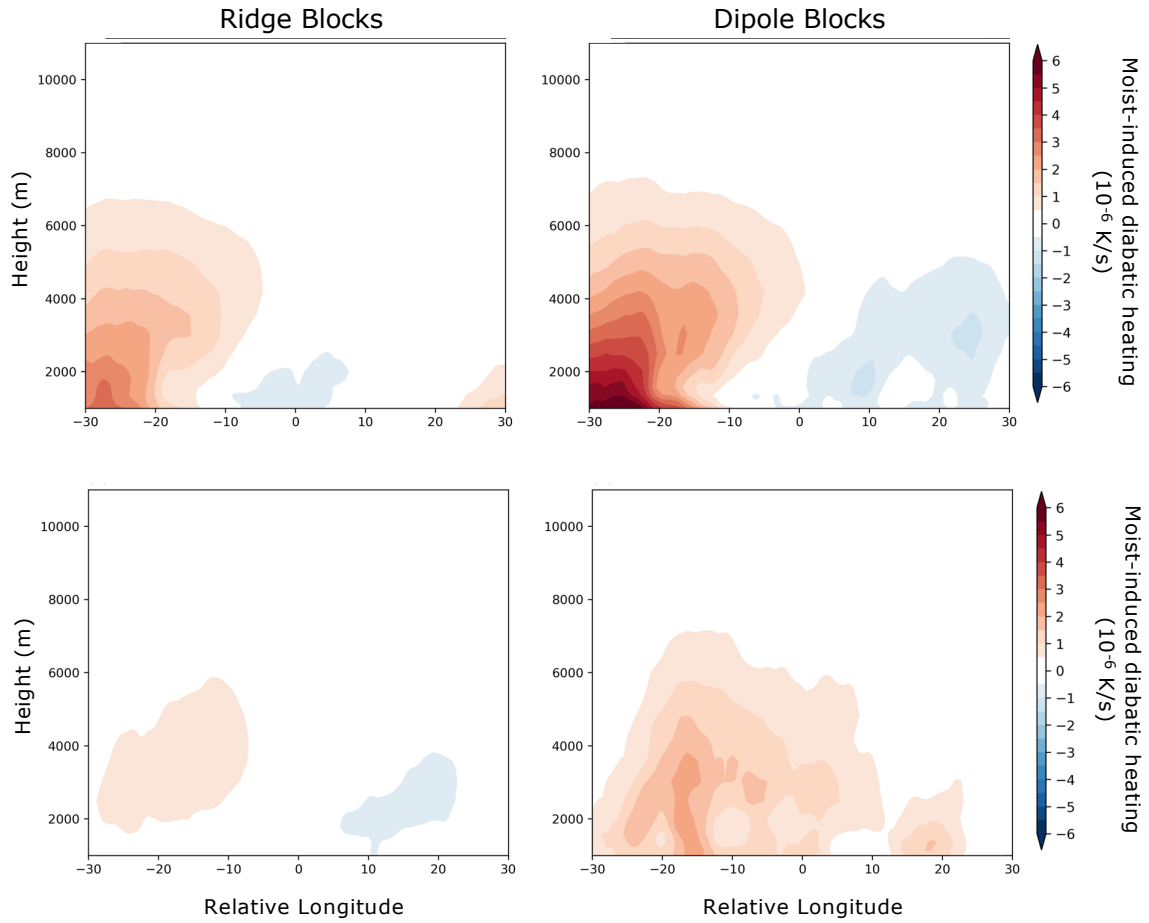


Figure 4.6: Composites of the vertical structure of moisture-induced diabatic heating around ridge and dipole blocks over the Euro-Atlantic (a, b) and North Pacific (c, d) domains from 1950–2024.

Temporal Evolution of Moisture-Induced Diabatic Heating in the Euro-Atlantic and North Pacific Domains

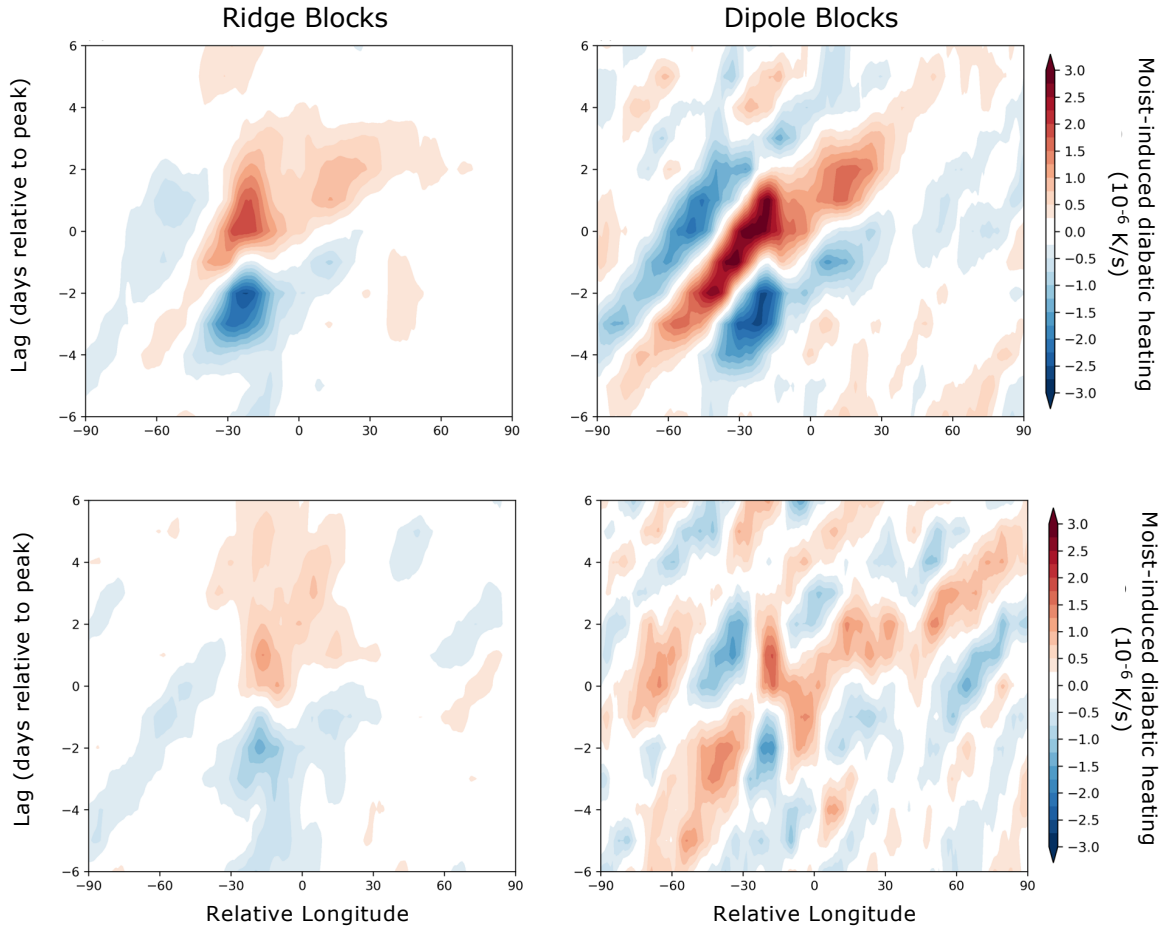


Figure 4.7: Hovmöller diagrams of moisture-induced diabatic heating of composited ridge and dipole blocks over the Euro-Atlantic (a, b) and North Pacific (c, d) domains from 1950–2024. Day 0 is the peak date of maximum blocking intensity.

4.2 Teleconnections

Teleconnection patterns like ENSO and the NAO are notable drivers of interannual and interdecadal blocking variability (Barriopedro et al., 2006; McKenna and Karamperidou, 2023; Renwick and Wallace, 1996; Scherrer et al., 2006; Shabbar et al., 2001; Wallace and Gutzler, 1981). Northern Hemisphere block frequency and duration composites presented by BC14 provide a useful avenue for comparison between this work’s dataset and previous literature, with the ability to expand analysis to include the role of blocking diversity.

4.2.1 El Niño Southern Oscillation

The spatial distributions of the frequency, duration, and intensity of blocking events in the Northern Hemisphere during extended winter are examined with respect to ENSO phase (Fig. 4.8). From 1950–2024, 21 El Niño and 31 La Niña winters were identified. In the EA, NP, and Eurasia, blocking events are significantly more frequent during La Niña than during El Niño phases (Fig. 4.8a). Blocks over Alaska are the exception to this, with a higher frequency during El Niño. The difference is greatest over the northeastern Atlantic off the western coast of the British Isles. The spatial pattern over the NP closely agrees with that of BC14, though at about half the magnitude. However, the increased occurrence of Alaskan blocks during El Niño is not reflected in their results. Similarly, BC14 reports no significant disparity in blocking frequency between ENSO phases over the EA domain, which does not agree with the pattern presented here. Additionally, they report an increase in blocking frequency over eastern Eurasia during El Niño phases, which is also contradictory. Over the Greenland region, eastern Europe, and the eastern NP, blocking events are significantly more persistent during El Niño than during La Niña phases (Fig. 4.8d). Conversely, blocking events are

less persistent near Iberia are significantly less persistent during El Niño than during La Niña phases. While the general spatial pattern over the EA roughly matches that reported by BC14, they observe a higher persistence in NP blocks during LN, which is not seen here. Additionally, the Iberian pattern is not shown by BC14 to be robust. Over Eurasia, the western EA, and the eastern NP, blocking events are significantly less intense during El Niño than during LN, while the opposite is true near the intermediate EA and NP (Fig. 4.8g).

As an expansion of the original BC14 study, composites of ridge and dipole blocks are examined separately. Ridge block frequency is significantly lower over the EA and Eurasia during El Niño than during La Niña (Fig. 4.8b). Conversely, blocks are more common over continental Alaska during El Niño than during La Niña phases. Dipole blocks exhibit much smaller disparities between the two phases (Figs. 4.8c). Dipole blocks are more frequent around the Arctic Ocean and the Mediterranean Sea during El Niño than during LN, and less frequent across the eastern NP and a small portion of the eastern EA. Ridge blocks exhibit significantly higher persistence in the northwest EA and eastern NP during El Niño than during La Niña phases, and lower persistence over the southern extent of the EA, as well as Siberia (Fig. 4.8e). There is a significantly higher persistence of dipole blocks in the GA and Greenland regions during El Niño than during La Niña phases, and lower persistence over western Europe and the high-latitude BS region (Fig. 4.8f). Ridge blocks exhibit significantly lower intensity over Eurasia, the continental Western Pacific region, and the eastern NP during El Niño than during LN, while the BS region and EA see more intense blocking (Figs. 4.8h). Dipole blocks exhibit significantly weaker blocking across Eurasia and the high-latitude NP, as well as over sporadic regions in the EA during El Niño than during La Niña phases (Figs. 4.8i).

Blocking Frequency, Duration, and Intensity by ENSO Phase (1950-2024)

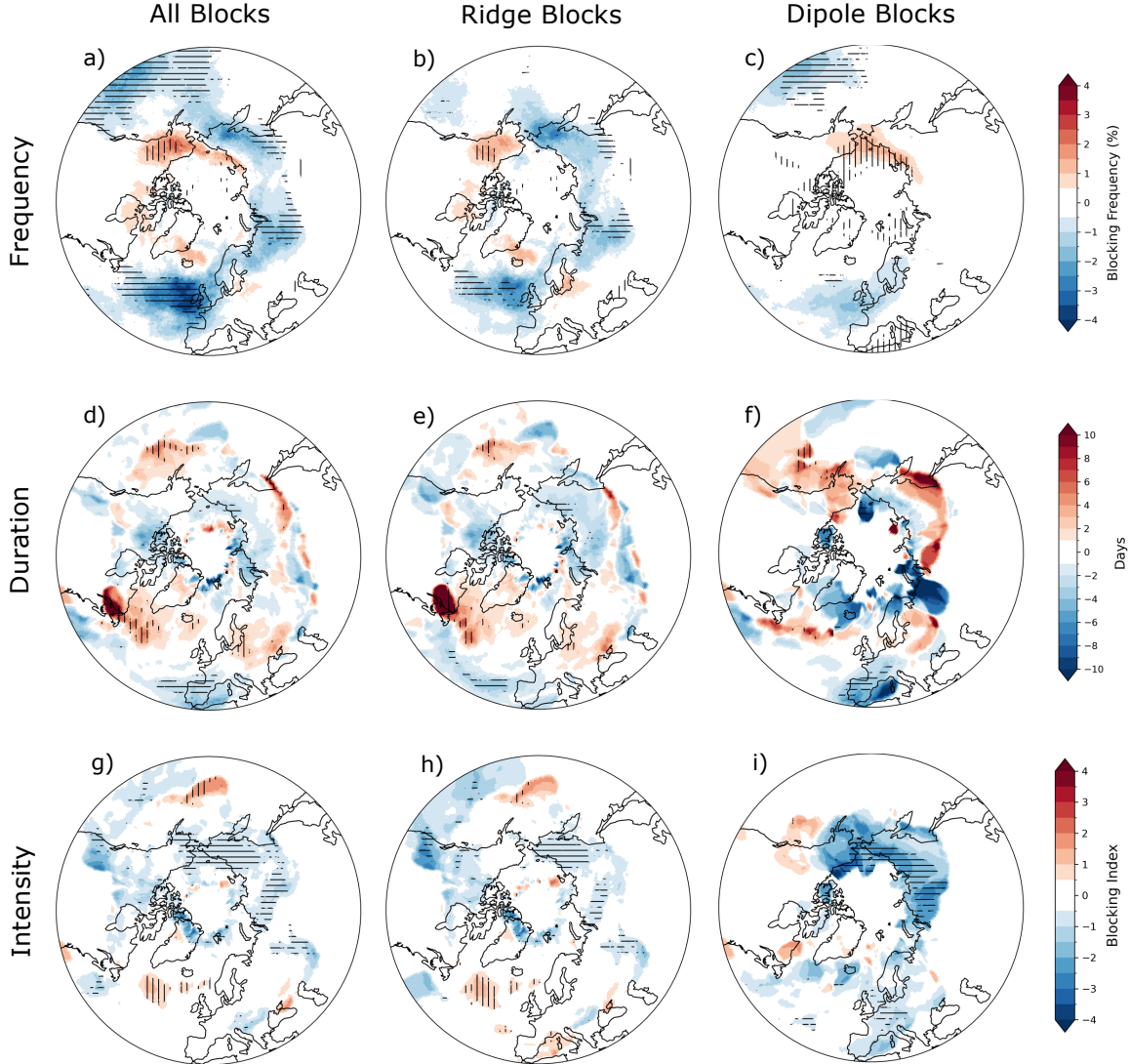


Figure 4.8: ENSO difference composites (El Niño minus La Niña) of extended winter (NDJFM) frequency (a-c), duration (d-f), and intensity (g-i) of all (a, d, g), ridge (b, e, h), and dipole (c, f, i) blocks in the Northern Hemisphere from 1950–2024. Cross-hatched areas with vertical (horizontal) lines indicate above (below) normal values that are statistically significant at the 95% confidence level.

4.2.2 North Atlantic Oscillation

The extended winter characteristics of blocking events in the Northern Hemisphere are examined with respect to NAO phase (Fig. 4.9). From 1950–2024, 47 NAO+ and 27 NAO- phases were identified. In the EA, blocks are more frequent around the Azores during NAO+, and around Greenland during NAO- (Fig. 4.9a). This is consistent with the definitional NAO pattern, which exhibits a persistent Azores high during NAO+ and subpolar high during NAO-. These two frequency anomalies in the domain each consist almost entirely of one flow pattern, with the Azores (subpolar) high dominated by dipole (ridge) blocks (Figs. 4.9b and 4.9c). Outside of the EA, there is a significantly lower blocking frequency over Siberia and a higher frequency over the Gulf of Alaska during NAO+ than during NAO-. This is primarily driven by ridge blocks. Blocking events are more persistent over the southern extent of the Greenland region and the northern NP during NAO+ than during NAO- (Fig. 4.9d). Additionally, they are less persistent over the southern extent of the NP and eastern Eurasia during NAO+ than during NAO-. Ridge blocks exhibit a higher persistence in the NP during NAO+ than during NAO-, along with a lower persistence in Eurasia that is paired with a slight negative anomaly over the Scandinavian region. (Fig. 4.9e). Dipole blocks are more persistent in the EA and less persistent in the NP during NAO+ than during NAO- (Fig. 4.9f). Blocking events are more intense over the Northern NP and overland Greenland during NAO+ than during NAO- (Fig. 4.9g). They are also slightly weaker in some parts of the eastern EA during NAO+ than during NAO-. This discrepancy is reflected by ridge blocks, which share a similar pattern, along with weaker intensities near the southern extent of the Gulf of Alaska region during NAO+ than NAO- (Figs. 4.9h). Dipole blocks are more intense across the EA during NAO+ than during NAO- (Figs. 4.9i).

Blocking Frequency, Duration, and Intensity by NAO Phase (1950-2024)

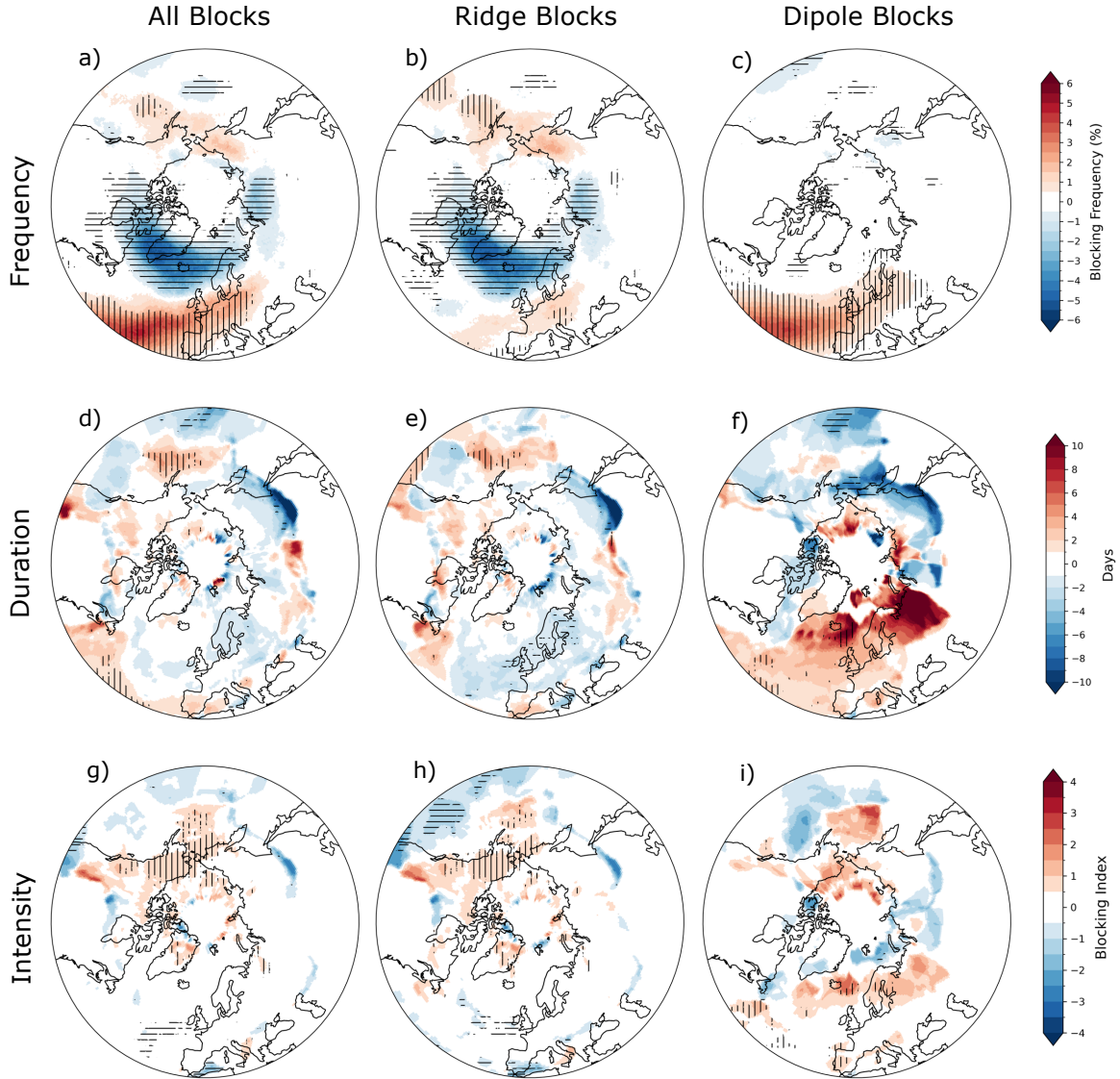


Figure 4.9: NAO difference composites (NAO+ minus NAO-) of extended winter (ND-JFM) frequency (a-c), duration (d-f), and intensity (g-i) of all (a, d, g), ridge (b, e, h), and dipole (c, f, i) blocks in the Northern Hemisphere from 1950–2024. Cross-hatched areas with vertical (horizontal) lines indicate above (below) normal values that are statistically significant at the 95% confidence level.

Chapter 5

Discussion

The climatological characteristics of Northern Hemisphere blocking events identified via our novel detection algorithm have been described, along with the seasonal and geographical variability of these characteristics. Interannual variability and linear trends from 1950–2024 were also observed. Additionally, relationships with dynamical drivers and teleconnections were examined and compared with established literature. Discussion of these results is presented in this section.

5.1 Blocking Characteristics

The 75-year dataset of Northern Hemisphere blocking events identified via our novel detection algorithm exhibits a frequency distribution in which blocks over oceanic domains (i.e., Euro-Atlantic (EA) and North Pacific (NP)) are more frequent than blocks over continental domains (i.e., Eurasia and North America) (Fig. 3.1). Over the full year, 47.0% of blocks occur over the EA, 34.9% over the NP, and 18.1% over the continental domains. Published literature that employs detection algorithms derived from the method developed by TM90 also note a primary blocking prevalence over the oceanic regions. However, there is some disagreement about which oceanic domain is the primary blocking sector, with studies split between the EA (Barriopedro et al., 2006; Cheung et al., 2013; Nejad et al., 2022) or the NP (Davini et al., 2012; Tyrllis et al., 2021). These factions can be distinguished by two common differences in their

blocking detection algorithm. First, studies that observe the highest frequency in the NP filter out low-latitude blocking (LLB) events as described in Section 2.2.1. While LLBs cause overestimation of blocking frequency in both oceanic domains, the effect is more pronounced on the EA domain (Davini et al., 2012). If frequency is evaluated as a function of longitude rather than a 2-dimensional array, this issue is obscured, leading to a weighted distribution towards the EA. Studies that employ a 2D view of blocking show this more clearly (Davini et al., 2012; Scherrer et al., 2006; Tyrllis et al., 2021), with the highest frequency in the EA centered around the southern extent of the analysis region (around 35°N) where LLB events occur. Second, studies that observe the highest frequency in the EA implement a third blocking criterion first employed by Barriopedro et al. (2006) in addition to criteria (2.3):

$$Z(\lambda, \phi_0) - \overline{Z}(\lambda, \phi_0) > 0. \quad (5.1)$$

This requires the geopotential height anomaly at a point, defined as the difference between the geopotential height at a specific day and the geopotential height for that day of the year averaged over the analyzed period, to be positive. Studies that note the highest frequency in the NP do not implement this additional criterion.

Because the algorithm employed in this study utilizes LLB filtering and does not implement criterion (5.1), the our dataset should exhibit the highest blocking frequency in the NP rather than the EA, which is not the case. However, this study differs from prior literature in that our algorithm imposes a hard cutoff for the maximum spatial areas that blocking events may achieve over their lifetime – $7.5 \times 10^6 \text{ km}^2$. As observed by Pinheiro et al. (2019), NP blocks identified via the AGP index (from Scherrer et al. (2006) and adapted from TM90) are the largest among all domains when no bounds are implemented, with an upper quartile around $7 \times 10^6 \text{ km}^2$. This contrasts with the

EA and continental domains, which exhibit upper quartiles around $5 \times 10^6 \text{ km}^2$ and $3 \times 10^6 \text{ km}^2$, respectively. Consequently, a substantial number of NP blocking events may be excluded from the dataset, more so than in other domains. The distribution of maximum area of blocking events (Fig. 3.7) exhibits an annual range in the NP that is only slightly larger than that of Eurasian blocks, indicating that the upper bound had an impact on the extent of NP blocking events represented in the dataset. The upper bound was defined subjectively based on the minimum area at which blocking events began to exhibit “unphysical” structures. As an example, many events with maximum areas above the upper bound would split into multiple blocked regions that spanned the entire longitudinal extent of the Northern Hemisphere encompassing multiple distinct meridional-dominant patterns. This result indicates that further examination of an appropriate upper bound may be pertinent.

As for blocking diversity, ridge blocks are the dominant flow pattern among Northern Hemisphere blocks, accounting for 75.8% of events. They are consistently larger, stronger, and more persistent than their dipole counterparts (Figs. 3.6, 3.8, 3.10). Additionally, oceanic domains host the majority of dipole blocking events while blocking events across Eurasia are nearly entirely ridge-type blocks (Fig. 3.4). These characteristics are supported by LW25. However, the mean central latitude of dipole blocks is considerably lower than what was observed by LW25. Consequently, regions that exhibit a high incidence of dipole blocks in LW25, mainly the Labrador Sea and the northern extent of the Gulf of Alaska, are instead dominated by ridge blocks. This is evidence of a potential issue with the procedure for classifying blocking events into the two flow patterns, which is likely due to incongruence in how LW25’s blocking detection method represents blocking structures and how they are represented here. Criteria (2.3) use reversals in meridional geopotential height gradients, which are representative of a block’s central anticyclone. This excludes the cyclone(s) associated with the

block. LW25’s detection method uses Z_{500} -based local wave activity (LWA) expressed by Equation (2.6). Specifically, they identify blocks as regions in which the LWA of contiguous points exceed the median of the meridional maximum LWA (i.e., the maximum LWA along a specific longitude) over the entire analyzed period. As Equation (2.6) describes, LWA encompasses both the anticyclonic and cyclonic features associated with a block. When blocks in our dataset are categorized into flow patterns via LWA, only the blocked points (which are inherently anticyclonic) are included, thereby underestimating LWA_C (Equation 2.8) and potentially leading to misclassification of dipole blocks as ridges in some cases. This underestimation would be more apparent at higher latitudes, where poleward meandering of Rossby waves is more likely to produce stronger anticyclones than at lower latitudes, increasing LWA_A (Equation 2.8) in the region identified as blocked in this study’s dataset. This presents a limitation for analysis that is dependent on separating blocks by flow pattern.

5.2 Diabatic Heating

With the characteristics of our blocking dataset defined, it is employed to examine the physical mechanisms relevant to blocking. First, moisture-induced diabatic heating is analyzed. As noted in Section 2.3.3, this term only describes the temperature tendency due to local latent heating, though it is referred to as ”moisture-induced diabatic heating” for the purpose of consistency with LW25. The observations described in Section 4.1 diverge substantially from those of LW25. Mainly, the magnitude of heating is considerably smaller than that of LW25, which is likely due to model bias. LW25 employed the Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2; Gelaro et al., 2017) model for analysis, which exhibits a positive specific humidity bias relative to ERA5 that is maximized around 500 hPa (Johnston

et al., 2021; Serra et al., 2023). Additionally, LW25 does not report any diabatic cooling in their composites, though this may be by ambiguous since they use a color bar that has a minimum at zero but is open-bounded. Some differences are likely due to the aforementioned incongruencies in blocking identification, potentially resulting in misclassification of blocking types. Primarily, this would affect the composited 500-hPa geopotential height fields for each flow pattern. The composited structure of ridge blocks is as expected, with a strong central high. There is also a discernable low that resides about 15–20 degrees south of the block center. This may be due to the inclusion of high-latitude dipoles, which would feature a cyclone equatorward of the block center. Dipole blocks exhibit a more prominent discrepancy with LW25, featuring a weak dipole structure with no closed contours. One reason for this discrepancy is that because block centers are calculated based on the average coordinates of the region identified as blocked, the composite is focused on the blocking anticyclone. Meanwhile, LW25’s composite is focused on the middle of the full blocking structure, including both the poleward high and equatorward low. Another reason may be that, because dipole blocks occur at lower latitudes on average in this dataset, associated cyclones are likely much weaker than those identified by LW25. This is due to further separation from the main region of Rossby wave circulation than higher latitude blocks, requiring greater deviation from regular zonal flow for strong cyclones to be produced.

Weakened cyclones associated with low-latitude dipole blocks are also a possible reason for the similar spatial structure in moisture-induced diabatic heating between ridge and dipole blocks. Because cyclone growth is limited at lower latitudes, large-scale moisture-induced diabatic heating equatorward of dipole block centers would be rare. The leading edges of troughs upstream of the anticyclonic regions of blocks would then be the primary region for storm track activity around low-latitude dipole blocks. Therefore, moisture-induced diabatic heating would be maximized upstream of these

blocks.

Another significant discrepancy between Figure 4.1 and LW25 is the temporal evolution of moisture-induced diabatic heating around both ridge and dipole blocks. Specifically, while the general structure of the evolution is comparable, the magnitudes are reversed, with cooling occurring during the early stages of formation and heating around the later stages of decay (Figs. 4.1e and 4.1f). This sequence is in stark contrast to the foundational literature connecting latent heating to atmospheric blocking, which consistently observe enhanced latent heating before and during blocking formation (Liu and Wang, 2025; Pfahl et al., 2015; Steinfeld et al., 2020; Yanai et al., 1973). The reason for this reversal is uncertain, and is an avenue for further study.

A primary driver for the seasonal variation in the spatiotemporal structure of moisture-induced diabatic heating described by 4.1 may be the seasonal fluctuation in geographical blocking distribution across the Northern Hemisphere. The spatial structures of moisture-induced diabatic heating around EA blocks are stronger and more spatially coherent than those of NP blocks (Figs. 4.5 and 4.6), potentially due to differences in the location of storm tracks in relation to blocking events over both domains. In the EA, storm tracks are generally oriented upstream of blocks, while in the NP, they are situated equatorward (Hoskins and Hodges, 2019). As such, the latent heating associated with storm tracks may be stronger and more coherent upstream of blocking events in the EA than in the NP. While both blocking and storm track distribution shift seasonally, this relationship remains consistent. As such, latent heating associated with storm tracks may be stronger and more spatially coherent upstream of blocking events in the EA than the NP, regardless of season. This is reflected by the moisture-induced diabatic heating maximizing in autumn, as the season exhibits the highest proportion of EA to NP blocking events throughout the year (Table 3.1). This is also consistent with the sporadic structure of mid-tropospheric diabatic heating in

summer, as it is the only season to feature more NP than EA blocks. The summertime structure is likely also influenced by the large number of Eurasian blocks that occur during the season. This may reduce the magnitude of latent heating overall due to detachment from oceanic sources of moisture over the continental domain.

5.3 Teleconnections

5.3.1 El Niño Southern Oscillation

The contrast between the blocking frequency distributions described in Section 4.2 and those of BC14 are consistent with other studies utilizing non-TM90 based blocking detection methods (McKenna and Karamperidou, 2023; Renwick and Wallace, 1996). However, Barriopedro et al. (2006) found phase discrepancies closely matching Figure 4.8a using a TM90-based detection method, though they were only examined longitudinally. The contrast between our blocking duration distribution observations and those of BC14 are consistent with other relevant literature, regardless of detection method (Barriopedro et al., 2006; McKenna and Karamperidou, 2023; Renwick and Wallace, 1996). As for blocking intensity, phase discrepancies across the Northern Hemisphere are not well studied in relevant literature, although observations from Barriopedro et al. (2006) generally match our observations. Future work into the factors resulting in TM90 based blocking detection methods yielding ENSO-blocking relationships that differ from non-TM90 based methods may be pertinent.

5.3.2 North Atlantic Oscillation

The discrepancy in extended winter EA blocking frequency distribution between NAO+ and NAO- phases (Fig. 4.9a) is consistent with those of previous studies utilizing TM90

based blocking detection methods (Scherrer et al., 2006; Shabbar et al., 2001). A notable observation that has not been examined compared to relevant literature on the connection between the NAO and Northern Hemisphere blocking is the apparent role of blocking diversity in the variation of EA blocking frequency during NAO phases. Specifically, only high-latitude EA ridge blocks exhibit a lower frequency during NAO+ than during NAO- phases, while only low-latitude EA ridge blocks exhibit a higher frequency during NAO+ than during NAO- phases. Relevant literature suggests that the inverse of this relationship should be observed, as NAO- phases promote cyclonic wave breaking (Luo et al., 2008). Because dipole blocks feature stronger cyclonic potential vorticity anomalies than ridge blocks (Liu and Wang, 2025; Woollings et al., 2018), dipole blocking should be more frequent during NAO- phases than NAO+. The observed relationship may be influenced by the potential misclassification of flow patterns within this study. Another notable observation is the enhancement of all examined variables of blocking events (driven by ridge blocks), in the Gulf of Alaska region during NAO+ compared to NAO- phases. This connection could possibly be rooted in the Pacific-North American (PNA) pattern, the negative phase of which is known to promote persistent ridging in the Gulf of Alaska (Wallace and Gutzler, 1981). The NAO and PNA may have some interaction, though this has not been conclusively established (Baxter and Nigam, 2013). Both the role of blocking diversity in the relationship between the NAO and blocking and the interaction between the PNA and NAO may be worthwhile avenues for future study using an improved flow type classification method.

Chapter 6

Summary and Conclusions

This thesis used ERA5 500 hPa geopotential height data to develop a novel detection algorithm for atmospheric blocking events in the Northern Hemisphere from 1950–2024. The algorithm was based on the blocking detection metric developed by Tibaldi and Molteni (1990) and adapted D’Andrea et al. (1998), Scherrer et al. (2006), and Davini et al. (2012). Additional metrics to expand the geographical extent of the target analysis region and filter erroneously detected flow patterns were included. A three-dimensional mapping tool called TempestExtremes (Ullrich et al., 2021) was employed to incorporate the full spatiotemporal evolution of blocking events in our identification process. Finally, a method proposed by Liu and Wang (2025) to classify blocking flow patterns as either ridge or dipoles was included. The resulting data set of Northern Hemisphere blocking events exhibited characteristics (i. e., frequency, spatial distribution, duration, maximum spatial area, and intensity) that were largely comparable to datasets produced by similar TM90-based detection algorithms. The seasonal and regional variations of these characteristics were also generally corroborated. A statistically significant increase in wintertime dipole blocking events over the Euro-Atlantic domain was observed. North Pacific blocks exhibited a significant increase in summertime frequency and annual median duration, along with a decrease in annual median intensity. Trends in North Pacific blocking were found to vary between the Bering Sea and Gulf of Alaska regions.

Moisture-induced diabatic heating was observed primarily upstream of both ridge

and dipole blocking events in the Northern Hemisphere. Additionally, diabatic cooling was observed during the early stages of the blocking life cycle, which transitioned to warming in later stages. These results diverge from those observed by LW25. Blocking events exhibited the strongest diabatic heating in autumn, as well as the Euro-Atlantic domain. This may correlate with the distribution of storm track activity around blocking events. Composites of the discrepancies in the spatial distribution of Northern Hemisphere blocking frequency between ENSO phases contrasted with those observed by BC14. However, they were comparable to observations of blocks detected via a TM90-based algorithm. Discrepancies in blocking duration between ENSO phases also differed from BC14. NAO composites indicated that blocking flow pattern type (i.e., ridge vs. dipole) may play a role in the variation of Euro-Atlantic blocking frequency between NAO phases.

This thesis is limited by a misstep in the differentiation of ridge and dipole blocks by our blocking detection algorithm. Due to incongruities in the representation of blocking flow patterns between our TM90-based metric and the metric employed by LW25, the flow type of blocking events may be incorrectly classified in some cases. While the specific impacts of this issue have not been elucidated, it is probable that observations presented in this thesis relating to the characteristics of ridge and dipole blocks may be skewed.

This thesis is a first step in the development of a novel approach to detect atmospheric blocking events, with consideration for the spatial and temporal evolution of blocking flow patterns. Future studies may focus on improvements that can be made to the accuracy of the novel detection algorithm presented here. These may include a more thorough characterization of the strengths and weakness of the algorithm, tweaking of identification and filtering criteria, and rectification of the block type classification process. Additionally, further comparison with other blocking detection methods

will be conducted. This will include comparison of the observed relationships between blocking and relevant dynamics and teleconnections.

Reference List

- Anstey, J. A., and Coauthors, 2013: Multi-model analysis of northern hemisphere winter blocking: Model biases and the role of resolution. *Journal of Geophysical Research: Atmospheres*, **118**, 3956–3971, <https://doi.org/10.1002/jgrd.50231>.
- Austin, J. F., 1980: The blocking of middle latitude westerly winds by planetary waves. *Quarterly Journal of the Royal Meteorological Society*, **106**, 327–350, <https://doi.org/10.1002/qj.49710644807>.
- Barnes, E. A., E. Dunn-Sigouin, G. Masato, and T. Woollings, 2014: Exploring recent trends in northern hemisphere blocking. *Geophysical Research Letters*, **41**, 638–644, <https://doi.org/10.1002/2013GL058745>.
- Barnston, A. G., and R. E. Livezey, 1987: Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Monthly Weather Review*, **115**, 1083–1126, [https://doi.org/10.1175/1520-0493\(1987\)115%3C1083:CSAPOL%3E2.0.CO;2](https://doi.org/10.1175/1520-0493(1987)115%3C1083:CSAPOL%3E2.0.CO;2).
- Barriopedro, D., and N. Calvo, 2014: On the relationship between ENSO, stratospheric sudden warmings, and blocking. *Journal of Climate*, **27**, 4704–4720, <https://doi.org/10.1175/JCLI-D-13-00770.1>.
- Barriopedro, D., R. García-Herrera, A. R. Lupo, and E. Hernández, 2006: A climatology of northern hemisphere blocking. *Journal of Climate*, **19**, 1042–1063, <https://doi.org/10.1175/JCLI3678.1>.
- Basu, A., A. Ghosh, N. Martin, and L. Pardo, 2020: Robust Wald-type tests in GLM with random design based on minimum density power divergence estimators. *Statistical Methods & Applications*, **30**, 973–1005, <https://doi.org/10.1007/s10260-020-00544-4>.
- Baxter, S., and S. Nigam, 2013: A subseasonal teleconnection analysis: PNA development and its relationship to the NAO. *Journal of Climate*, **26**, 6733–6741, <https://doi.org/10.1175/JCLI-D-12-00426.1>.
- Benedict, J. J., S. Lee, and S. B. Feldstein, 2004: Synoptic view of the north atlantic oscillation. *Journal of the Atmospheric Sciences*, **61**, 121–144, [https://doi.org/10.1175/1520-0469\(2004\)061<0121:SVOTNA>2.0.CO;2](https://doi.org/10.1175/1520-0469(2004)061<0121:SVOTNA>2.0.CO;2).
- Berggren, R., B. Bolin, and C. G. Rossby, 1949: An aerological study of zonal motion,

- its perturbations and break-down. *Tellus*, **1**, 14–37, <https://doi.org/10.1111%2Fj.2153-3490.1949.tb01257.x>.
- Biernat, K. A., L. F. Bosart, and D. Keyser, 2021: A climatological analysis of the linkages between tropopause polar vortices, cold pools, and cold air outbreaks over the central and eastern united states. *Monthly Weather Review*, **149**, 189–206.
- Black, E., M. Blackburn, G. Harrison, B. J. Hoskings, and J. Methven, 2006: Factors contributing to the summer 2003 european heatwave. *Weather*, **59**, 217–223, <https://doi.org/10.1256/wea.74.04>.
- Brunet, G., 1993: Empirical normal-mode analysis of atmospheric data. *Journal of the Atmospheric Sciences*, **51**, 932–952.
- Burkhardt, J. P., and A. R. Lupo, 2005: The planetary- and synoptic-scale interactions in a southeast pacific blocking episode using PV diagnostics. *Journal of Atmospheric Sciences*, **62**, 1901–1916.
- Burzdak, J. W., S. M. Cavallo, and D. B. Parsons, 2026: Characteristics and life cycles of anticyclonic tropopause polar vortices. *Monthly Weather Review*, **154**, 523–540, <https://doi.org/10.1175/MWR-D-24-0179.1>.
- Charney, J. G., and J. G. DeVore, 1979: Multiple flow equilibria in the atmosphere and blocking. *Journal of the Atmospheric Sciences*, **36**, 1205–1216, [https://doi.org/10.1175/1520-0469\(1979\)036%3C1205:MFEITA%3E2.0.CO;2](https://doi.org/10.1175/1520-0469(1979)036%3C1205:MFEITA%3E2.0.CO;2).
- Cheung, H. N., W. Zhou, H. Y. Mok, M. C. Wu, and Y. Shao, 2013: Revisiting the climatology of atmospheric blocking in the northern hemisphere. *Advances in Atmospheric Sciences*, **30**, 397–410, <https://doi.org/10.1007/s00376-012-2006-y>.
- Colucci, S. J., 1985: Explosive cyclogenesis and large-scale circulation changes: Implications for atmospheric blocking. *Journal of the Atmospheric Sciences*, **42**, 2701–2717, [https://doi.org/10.1175/1520-0469\(1985\)042%3C2701:ECALSC%3E2.0.CO;2](https://doi.org/10.1175/1520-0469(1985)042%3C2701:ECALSC%3E2.0.CO;2).
- Coxe, S., S. G. West, and L. S. Aiken, 2009: The analysis of count data: A gentle introduction to Poisson regression and its alternatives. *Journal of Personality Assessment*, **91**, 121–136, <https://doi.org/10.1080/00223890802634175>.
- Croci-Maspoli, M., and H. C. Davies, 2009: Key dynamical features of the 2005/06 european winter. *Monthly Weather Review*, **137**, 664–678, <https://doi.org/10.1175/2008MWR2533.1>.
- Croci-Maspoli, M., C. Schwierz, and H. C. Davies, 2007: A multifaceted climatology

- of atmospheric blocking and its recent linear trend. *Journal of the Atmospheric Sciences*, **72**, 2227–2240, <https://doi.org/10.1175/JCLI4029.1>.
- D’Andrea, F., S. Tibaldi, and M. Blackburn, 1998: Northern hemisphere atmospheric blocking as simulated by 15 atmospheric general circulation models in the period 1979–1988. *Climate Dynamics*, **14**, 385–407, <https://doi.org/10.1007/S003820050230>.
- Davini, P., C. Cagnazzo, S. Gualdi, and A. Navarra, 2012: Bidimensional diagnostics, variability, and trends of northern hemisphere blocking. *Journal of Climate*, **25**, 6496–6519, <https://doi.org/10.1175/JCLI-D-12-00032.1>.
- Dole, R. M., and N. D. Gordon, 1983: Persistent anomalies of the extratropical northern hemisphere wintertime circulation: Geographical distribution and regional persistence characteristics. *Monthly Weather Review*, **111**, 1567–1586, [https://doi.org/10.1175/1520-0493\(1983\)111<1567:PAOTEN>2.0.CO;2](https://doi.org/10.1175/1520-0493(1983)111<1567:PAOTEN>2.0.CO;2).
- Elliot, R. D., and T. B. Smith, 1949: A study of the effects of large blocking highs on the general circulation in the northern-hemisphere westerlies. *Journal of Meteorology*, **6**, 68–85, [https://doi.org/10.1175/1520-0469\(1949\)006%3C0068:ASOTEO%3E2.0.CO;2](https://doi.org/10.1175/1520-0469(1949)006%3C0068:ASOTEO%3E2.0.CO;2).
- Fennessy, M. J., and J. L. Kinter III, 2011: Climatic feedbacks during the 2003 european heat wave. *Journal of Climate*, **24**, 5953–5967, <https://doi.org/10.1175/2011JCLI3523.1>.
- Gabriel, A., and D. Peters, 2008: A diagnostic study of different types of rossby wave breaking events in the northern extratropics. *Journal of the Meteorological Society of Japan*, **86**, 613–631, <https://doi.org/10.2151/jmsj.86.613>.
- García-Herrera, R., J. Díaz, R. M. Trigo, J. Luterbacher, and E. M. Fischer, 2010: A review of the european summer heat wave of 2003. *Critical Reviews in Environmental Science and Technology*, **40**, 267–306, <https://doi.org/10.1080/10643380802238137>.
- Gelaro, R., W. McCarty, and M. J. Suárez, 2017: The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). *Journal of Climate*, **30**, 5419–5454, <https://doi.org/10.1175/JCLI-D-16-0758.1>.
- Gilbert, N., 2010: Russia counts environmental cost of wildfires. *Nature*, <https://doi.org/10.1038/news.2010.404>.
- Henderson, S., E. Maloney, and E. A. Barnes, 2016: The influence of the Madden-Julian Oscillation on northern hemisphere winter blocking. *Journal of Climate*, **29**,

4597–4616, <https://doi.org/10.1175/JCLI-D-15-0502.1>.

- Hersbach, H., B. Bell, and P. Berrisford, 2020: The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, **146**, 1999–2049, <https://doi.org/10.1002/qj.3803>.
- Horton, D. E., N. C. Johnson, D. Singh, L. Swain, B. Rajaratnam, and N. S. Diffenbaugh, 2015: Contribution of changes in atmospheric circulation patterns to extreme temperature trends. *Nature*, **522**, 465–469, <https://doi.org/10.1038/nature14550>.
- Hoskins, B. J., and S. P. D., 1987: A diagnostic study of the dynamics of the northern hemisphere winter of 1985–1986. *Quarterly Journal of the Royal Meteorological Society*, **113**, 759–778, <https://doi.org/10.1002/qj.49711347705>.
- Hoskins, B. J., and K. I. Hodges, 2019: The annual cycle of northern hemisphere storm tracks. part i: Seasons. *Journal of Climate*, **32**, 1743–1760, <https://doi.org/10.1175/JCLI-D-17-0870.1>.
- Huang, C. S. Y., and N. Nakamura, 2016: Local finite-amplitude wave activity as a diagnostic of anomalous weather events. *Journal of the Atmospheric Sciences*, **73**, 211–229, <https://doi.org/10.1175/JAS-D-15-0194.1>.
- Hudson, D., A. Oscar, H. H. Hendon, and A. G. Marshall, 2011: Bridging the gap between weather and seasonal forecasting: intraseasonal forecasting for australia. *Quarterly Journal of the Royal Meteorological Society*, **137**, 673–689, <https://doi.org/10.1002/qj.769>.
- Hwang, J., P. Martineau, S. W. Son, T. Miyasaka, and H. Nakamura, 2020: The role of transient eddies in north pacific blocking formation and its seasonality. *Journal of the Atmospheric Sciences*, **77**, 2453–2470, <https://doi.org/10.1175/JAS-D-20-0011.1>.
- Johnston, B. R., W. J. Randel, and J. P. Sjöberg, 2021: Evaluation of tropospheric moisture characteristics among COSMIC-2, ERA5 and MERRA-2 in the tropics and subtropics. *Remote Sensing*, **13**, <https://doi.org/10.3390/rs13050880>.
- Kautz, L. A., O. Martius, S. Pfahl, J. G. Pinto, A. M. Ramos, M. Sousa, and T. Woollings, 2022: Atmospheric blocking and weather extremes over the euro-atlantic sector - a review. *Weather and Climate Dynamics*, **3**, 305–336, <https://doi.org/10.5194/wcd-3-305-2022>.
- Kiranmayi, L., and E. D. Maloney, 2011: Intraseasonal moist static energy budget in reanalysis data. *Journal of Geophysical Research: Atmospheres*, **116**, <https://doi.org/10.1029/2011JD016031>.

- Kolstad, E. W., and C. H. O'Reilly, 2024: Causal oceanic feedbacks onto the winter NAO. *Climate Dynamics*, **62**, 4223–4236, <https://doi.org/10.1007/s00382-024-07128-y>.
- Kwon, Y., H. Seo, C. C. Ummenhofer, and T. M. Joyce, 2020: Impact of multidecadal variability in atlantic sst on winter atmospheric blocking. *Journal of Climate*, **33**, 867–892, <https://doi.org/10.1175/JCLI-D-19-0324.1>.
- Legras, B., and M. Ghil, 1985: Persistent anomalies, blocking and variations in atmospheric predictability. *Journal of the Atmospheric Sciences*, **42**, 433–471, [https://doi.org/10.1175/1520-0469\(1985\)042%3C0433:PABAVI%3E2.0.CO;2](https://doi.org/10.1175/1520-0469(1985)042%3C0433:PABAVI%3E2.0.CO;2).
- Lejenäs, H., and H. Økland, 1983: Characteristics of northern hemisphere blocking as determined from a long time series of observational data. *Tellus A*, **35**, 350–362, <https://doi.org/10.1111/j.1600-0870.1983.tb00210.x>.
- Lenggenhager, S., and O. Marius, 2019: Atmospheric blocks modulate the odds of heavy precipitation events in europe. *Climate Dynamics*, **53**, 4155–4171, <https://doi.org/10.1007/s00382-019-04779-0>.
- Leung, L. R., D. C. Bader, M. A. Taylor, and R. B. McCoy, 2020: An introduction to the E3SM special collection: Goals, science drivers, development, and analysis. *Journal of Advances in Modeling Earth Systems*, **12**, <https://doi.org/10.1029%2F2019MS001821>.
- Lillo, S. P., S. M. Cavallo, D. B. Parsons, and C. Riedel, 2021: The role of a tropopause polar vortex in the generation of the january 2019 extreme arctic outbreak. *Journal of the Atmospheric Sciences*, **78**, 2801–2821, <https://doi.org/10.1175/JAS-D-20-0285.1>.
- Liu, Z., and L. Wang, 2025: Blocking diversity causes distinct roles of diabatic heating in the northern hemisphere. *Nature Communications*, **16**, <https://doi.org/10.1038/s41467-025-60811-4>.
- Luo, D., T. Gong, and Y. Diao, 2008: Dynamics of eddy-driven low-frequency dipole modes. part iv: Planetary and synoptic wave-breaking processes during the NAO life cycle. *Journal of the Atmospheric Sciences*, **65**, 737–765, <https://doi.org/10.1175/2007JAS2440.1>.
- Luo, D., Y. Xiao, Y. Yao, A. Dai, I. Simmonds, and C. L. Franzke, 2016: Impact of ural blocking on winter warm arctic-cold eurasian anomalies. part i: Blocking-induced amplification. *Journal of Climate*, **29**, 3925–3947, <https://doi.org/10.1175/JCLI-D-15-0611.1>.

- Mariotti, A., R. M. Paolo, and M. Rixen, 2018: Progress in subseasonal to seasonal prediction through a joint weather and climate community effort. *npj Climate and Atmospheric Science*, **1**, <https://doi.org/10.1038/s41612-018-0014-z>.
- Martineau, P., G. Chen, and D. A. Burrows, 2017: Wave events: Climatology, trends, and relationship to northern hemisphere winter blocking and weather extremes. *Journal of Climate*, **30**, 5675–5697, <https://doi.org/10.1175/JCLI-D-16-0692.1>.
- Masato, G., B. J. Hoskins, and T. J. Woollings, 2011: Wave-breaking characteristics of midlatitude blocking. *Quarterly Journal of the Royal Meteorological Society*, **138**, 1285–1296, <https://doi.org/10.1002/qj.990>.
- Mass, C., D. Ovens, J. Christy, and R. Conrick, 2024: The pacific northwest heat wave of 25-30 june 2021: Synoptic/mesoscale conditions and the climate perspective. *Weather and Forecasting*, **29**, 275–291, <https://doi.org/10.1175/WAF-D-23-0154.1>.
- Matsueda, M., 2009: Blocking predictability in operational medium-range ensemble forecasts. *SOLA*, **5**, 113–116, <https://doi.org/10.2151/sola.2009029>.
- McIntyre, M. E., and T. N. Palmer, 1983: Breaking planetary waves in the stratosphere. *Nature*, **305**, 593–600, <https://doi.org/10.1038/305593a0>.
- McKenna, M., and C. Karamperidou, 2023: The impacts of El Niño diversity on northern hemisphere atmospheric blocking. *Geophysical Research Letters*, **50**, <https://doi.org/10.1029/2023GL104284>.
- Meehl, G. A., J. H. Richter, H. Teng, A. Capotondi, K. Cobb, F. Doblas-Reyes, M. G. Donat, and M. H. England, 2021: Initialized earth system prediction from subseasonal to decadal timescales. *Nature Reviews Earth & Environment*, **2**, <https://doi.org/10.1038/s43017-021-00155-x>.
- Millin, O. T., and J. C. Furtado, 2022: The role of wave breaking in the development and subseasonal forecasts of the february 2021 great plains cold air outbreak. *Geophysical Research Letters*, **49**, <https://doi.org/10.1029/2022GL100835>.
- Moore, R. W., O. Martius, and T. Spengler, 2010: The modulation of the subtropical and extratropical atmosphere in the pacific basin in response to the Madden-Julian Oscillation. *Monthly Weather Review*, **138**, 2761–2779, <https://doi.org/10.1175/2010MWR3194.1>.
- Mullen, S. L., 1987: Transient eddy forcing of blocking flows. *Journal of the Atmospheric Sciences*, **44**, 3–22, [https://doi.org/10.1175/1520-0469\(1987\)044%3C0003:TEFOBF%3E2.0.CO;2](https://doi.org/10.1175/1520-0469(1987)044%3C0003:TEFOBF%3E2.0.CO;2).

- Nakamura, H., M. Nakamura, and J. L. Anderson, 1997: The role of high- and low-frequency dynamics in blocking formation. *Monthly Weather Review*, **125**, 2074–2093, [https://doi.org/10.1175/1520-0493\(1997\)125%3C2074:TROHAL%3E2.0.CO;2](https://doi.org/10.1175/1520-0493(1997)125%3C2074:TROHAL%3E2.0.CO;2).
- Neal, E., C. S. Y. Huang, and N. Nakamura, 2022: The 2021 pacific northwest heat wave and associated blocking: Meteorology and the role of an upstream cyclone as a diabatic source of wave activity. *Geophysical Research Letters*, **49**, <https://doi.org/10.1029/2021GL097699>.
- Nejad, M. T., Z. Hejazizadeh, A. R. Lupo, and M. Saligheh, 2022: Spatio-temporal distribution of atmospheric blocking events in the northern and southern hemispheres. *Theoretical and Applied Climatology*, **150**, 491–505, <https://doi.org/10.1007/s00704-022-04175-5>.
- Pfahl, S., M. Schwierz, M. Croci-Maspoli, C. M. Grams, and H. Wernli, 2015: Importance of latent heat release in ascending air streams for atmospheric blocking. *Nature Geoscience*, **8**, 610–614, <https://doi.org/10.1038/ngeo2487>.
- Pinheiro, M. C., P. A. Ullrich, and R. Grotjahn, 2019: Atmospheric blocking and intercomparison of objective detection methods: flow field characteristics. *Climate Dynamics*, **53**, 4189–4216, <https://doi.org/10.1007/s00382-019-04782-5>.
- Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research: Atmospheres*, **108**, <https://doi.org/10.1029/2002JD002670>.
- Renwick, J. A., and M. J. Revell, 1999: Blocking over the south pacific and rossby wave propagation. *Monthly Weather Review*, **127**, 2233–2247, [https://doi.org/10.1175/1520-0493\(1999\)127%3C2233:BOTSPA%3E2.0.CO;2](https://doi.org/10.1175/1520-0493(1999)127%3C2233:BOTSPA%3E2.0.CO;2).
- Renwick, J. A., and J. M. Wallace, 1996: Relationships between north pacific wintertime blocking, El Niño, and the PNA pattern. *Monthly Weather Review*, **124**, 2071–2076, [https://doi.org/10.1175/1520-0493\(1996\)124<2071:RBNPWB>2.0.CO;2](https://doi.org/10.1175/1520-0493(1996)124<2071:RBNPWB>2.0.CO;2).
- Rex, D. F., 1950: Blocking action in the middle troposphere and its effect upon regional climate. *Tellus*, **2**, 196–211, <https://doi.org/10.1111/j.2153-3490.1950.tb00331.x>.
- Rivière, G., and I. Orlanski, 2007: Characteristics of the atlantic storm-track eddy activity and its relation with the north atlantic oscillation. *Journal of the Atmospheric Sciences*, **64**, 241–266, <https://doi.org/10.1175/JAS3850.1>.

- Sanders, F., and J. R. Gyakum, 1980: Synoptic-dynamic climatology of the "bomb". *Monthly Weather Review*, **108**, 1589–1606, [https://doi.org/10.1175/1520-0493\(1980\)108%3C1589:SDCOT%3E2.0.CO;2](https://doi.org/10.1175/1520-0493(1980)108%3C1589:SDCOT%3E2.0.CO;2).
- Santos, J. A., J. G. Pinto, and U. Ulbrich, 2009: On the development of strong ridge episodes over the eastern north atlantic. *Geophysical Research Letters*, **36**, <https://doi.org/10.1029/2009GL039086>.
- Scherrer, S. C., M. Croci-Maspoli, C. Schierz, and C. Appenzeller, 2006: Two-dimensional indices of atmospheric blocking and their statistical relationship with winter climate patterns in the euro-atlantic region. *International Journal of Climatology*, **26**, 233–249, <https://doi.org/10.1002/joc.1250>.
- Schierz, C., M. Croci-Maspoli, and H. C. Davies, 2004: Perspicacious indicators of atmospheric blocking. *Geophysical Research Letters*, **31**, <https://doi.org/10.1029/2003GL019341>.
- Serra, Y. L., S. A. Rutledge, K. Chudler, and C. Zhang, 2023: Rainfall and convection in ERA5 and MERRA-2 over the northern equatorial western pacific during PISTON. *Journal of Climate*, **36**, 845–863, <https://doi.org/10.1175/JCLI-D-22-0203.1>.
- Shabbar, A., J. Huang, and K. Higuchi, 2001: The relationship between the wintertime north atlantic oscillation and blocking episodes in the north atlantic. *International Journal of Climatology*, **21**, 355–369, <https://doi.org/10.1002/joc.612>.
- Shaposhnikov, D., and Coauthors, 2014: Mortality related to air pollution with the moscow heat wave and wildfire of 2010. *Epidemiology*, **25**, 359–364, <https://doi.org/10.1097/EDE.0000000000000090>.
- Shutts, G. J., 1983: The propagation of eddies in diffluent jetstreams: Eddy vorticity forcing of 'blocking' flow fields. *Quarterly Journal of the Royal Meteorological Society*, **109**, 737–761, <https://doi.org/10.1002/qj.49710946204>.
- Sousa, P. M., D. Barriopedro, R. García-Herrera, T. Woollings, and R. M. Trigo, 2021: A new combined detection algorithm for blocking and subtropical ridges. *Journal of Climate*, **34**, 7735–7758, <https://doi.org/10.1175/JCLI-D-20-0658.1>.
- Steinfeld, D., M. Boettcher, R. Forbes, and S. Pfahl, 2020: The sensitivity of atmospheric blocking to upstream latent heating: Numerical experiments. *Weather and Climate Dynamics*, **1**, 405–426, <https://doi.org/10.5194/wcd-1-405-2020>.
- Steinfeld, D., and S. Pfahl, 2019: The role of latent heating in atmospheric blocking dynamics: a global climatology. *Climate Dynamics*, **53**, 6159–6180, <https://doi.org/>

10.1007/s00382-019-04919-6.

- Tibaldi, S., and F. Molteni, 1990: On the operational predictability of blocking. *Tellus*, **42**, 343–365, <https://doi.org/10.3402/tellusa.v42i3.11882>.
- Tilly, D. E., A. R. Lupo, C. J. Melick, and P. S. Market, 2008: Calculated height tendencies in two southern hemisphere blocking and cyclone events: The contribution of diabatic heating to block intensification. *Monthly Weather Review*, **136**, 3568–3578, <https://doi.org/10.1175/2008MWR2374.1>.
- Tyrllis, E., J. Bader, E. Manzini, and D. Matei, 2021: Reconciling different methods of high-latitude blocking detection. *Quarterly Journal of the Royal Meteorological Society*, **147**, 1070–1096, <https://doi.org/10.1002/qj.3960>.
- Ullrich, P., C. Zarzycki, E. McClenny, M. Pinheiro, A. Stansfield, and K. Reed, 2021: Tempestextremes v2.1: a community framework for feature detection, tracking, and analysis in large datasets. *Geoscientific Model Development*, **14**, 5023–5048, <https://doi.org/10.5194/gmd-14-5023-2021>.
- Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in the geopotential height field during the northern hemisphere winter. *Monthly Weather Review*, **109**, 784–812, [https://doi.org/10.1175/1520-0493\(1981\)109<0784:TITGHF>2.0.CO;2](https://doi.org/10.1175/1520-0493(1981)109<0784:TITGHF>2.0.CO;2).
- Wang, L., and Coauthors, 2026: Gaps and ways forward in atmospheric blocking and extreme weather research. *Nature Communications*, **17**, <https://doi.org/10.1038/s41467-026-70487-z>.
- Wazneh, H., P. Gachon, R. Laprise, A. de Vernal, and B. Tremblay, 2021: Atmospheric blocking events in the north atlantic: trends and links to climate anomalies and teleconnections. *Climate Dynamics*, **56**, 2199–2221, <https://doi.org/10.1007/s00382-020-05583-x>.
- Wegren, S. K., 2013: Food security and russia’s 2010 drought. *Climate Dynamics*, **52**, 140–156, <https://doi.org/10.2747/1539-7216.52.1.140>.
- White, R. H., and Coauthors, 2017: Potential applications of subseasonal-to-seasonal (s2s) predictions. *Meteorological Application*, **24**, 315–325, <https://doi.org/10.1002%2Fmet.1654>.
- White, R. H., and Coauthors, 2023: The unprecedented pacific northwest heatwave of june 2021. *Nature Communications*, **14**, <https://doi.org/10.1038/s41467-023-36289-3>.

- 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. *Journal of Climate*, **15**, 3459–3473, [https://doi.org/10.1175/1520-0442\(2002\)015<3459:TCOBAF>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<3459:TCOBAF>2.0.CO;2).
- Woollings, T., and Coauthors, 2018: Blocking and its response to climate change. *Current Climate Change Reports*, **4**, 287–300, <https://doi.org/10.1007/s40641-018-0108-z>.
- Yamazaki, A., and H. Itoh, 2013: Vortex-vortex interactions for the maintenance of blocking. part i: The selective absorption mechanism and a case study. *Journal of the Atmospheric Sciences*, **70**, 725–742, <https://doi.org/10.1175/JAS-D-11-0295.1>.
- Yanai, M., S. Esbensen, and J.-H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *Journal of the Atmospheric Sciences*, **30**, 611–627, [https://doi.org/10.1175/1520-0469\(1973\)030<0611:DOBPOT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1973)030<0611:DOBPOT>2.0.CO;2).
- Zhang, C., D. Wang, L. Yao, Z. Wu, Q. Ma, Y. Li, and P. Wang, 2024: Contrasts of large-scale moisture and heat budgets between different sea areas of the south china sea and adjacent land. *Journal of Applied Meteorology and Climatology*, **63**, 105–124, <https://doi.org/10.1175/JAMC-D-23-0084.1>.
- Zhu, H., and H. H. Hendon, 2014: Role of large-scale moisture advection for simulation of the MJO with increased entrainment. *Quarterly Journal of the Royal Meteorological Society*, **141**, 2127–2136, <https://doi.org/10.1002/qj.2510>.