



Local and Remote Atmospheric Circulation Drivers of Arctic Change: A Review

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Arctic Amplification is a fundamental feature of past, present, and modelled future climate. However, the causes of this “amplification” within Earth’s climate system are not fully understood. To date, warming in the Arctic has been most pronounced in autumn and winter seasons, with this trend predicted to continue based on model projections of future climate. Nevertheless, the mechanisms by which this will take place are numerous, interconnected, and complex. Will future Arctic Amplification be primarily driven by local, within-Arctic processes, or will external forces play a greater role in contributing to changing climate in this region? Motivated by this uncertainty in future Arctic climate, this review seeks to evaluate several of the key atmospheric circulation processes important to the ongoing discussion of Arctic amplification, focusing primarily on processes in the troposphere. Both local and remote drivers of Arctic amplification are considered, with specific focus given to high-latitude atmospheric blocking, poleward moisture transport, and tropical-high latitude subseasonal teleconnections. Impacts of circulation variability and moisture transport on sea ice, ice sheet surface mass balance, snow cover, and other surface cryospheric variables are reviewed and discussed. The future evolution of Arctic amplification is discussed in terms of projected future trends in atmospheric blocking and moisture transport and their coupling with the cryosphere. As high-latitude atmospheric circulation is strongly influenced by lower-latitude processes, the future state of tropical-to-Arctic teleconnections is also considered.

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INTRODUCTION: ARCTIC AMPLIFICATION—LOCAL AND REMOTE CAUSES

Arctic-amplified near-surface atmospheric warming is a fundamental feature of past climate warming periods, present-day warming trends, and modeled future changes to the Earth’s climate system. However, the causes of this “Arctic amplification” are not fully understood (Serreze and Barry, 2011). Amplified Arctic warming has been most pronounced during autumn and winter, and model simulations project this will remain the case in future warming scenarios (Serreze and Francis, 2006; Lu and Cai, 2009; Serreze et al., 2009; Screen and Simmonds, 2010; Bintanja and van der Linden, 2013; Cohen et al., 2014; Dai et al., 2019). A number of interconnected physical processes, occurring within and external to the Arctic and with distinct seasonal variability, have been identified as contributing to Arctic amplification (Taylor et al., 2013; Yoshimori et al.,

2014a; Kim and Kim, 2017; Lang et al., 2017; Goosse et al., 2018; Park et al., 2018; Stuecker et al., 2018; Ding et al., 2019).

The earliest-identified cause of enhanced warming is the ice-albedo (or surface-albedo) feedback, whereby some initial warming reduces polar ice and snow cover and causes a greater fraction of incoming solar radiation to be absorbed, which further accelerates warming and albedo reduction (Budyko, 1969; Cess et al., 1991; Serreze et al., 2009). Other local feedback processes that may contribute to enhanced warming in the absence of extra-Arctic influence include the lapse rate and Planck feedbacks (Manabe and Wetherald, 1975; Crook et al., 2011; Pithan and Mauritsen, 2014; Hahn et al., 2020; Previdi et al., 2020), as well as cloud and water vapor feedbacks (Graversen and Wang, 2009; Cox et al., 2015; Kay et al., 2016; Södergren et al., 2018; Huang et al., 2019; Feldl et al., 2020; Middlemas et al., 2020) in an atmosphere moistened by sea ice decline (Boisvert et al., 2015; Jun et al., 2016; Taylor et al., 2018; Rinke et al., 2019b). Extra-Arctic processes, in particular changes to large-scale atmospheric and oceanic circulation and related changes in poleward atmospheric moist and dry static energy transport (e.g., Yang et al., 2010; Alexeev and Jackson, 2013; Zhang et al., 2013; Graversen and Burtu, 2016; Gong et al., 2017; Yoshimori et al., 2017), also contribute to Arctic amplification and are entangled with intra-Arctic feedbacks in complex ways. For example, cyclones facilitating poleward warm, moist air from lower latitudes may induce an initial retreat of sea ice, which strengthens the local ice-albedo feedback. This in turn amplifies the lapse rate feedback, which can be understood as a manifestation of accentuated lower-tropospheric warming dictated by the surface temperature change (Boeke et al., 2021). Feldl et al. (2020) and Boeke et al. (2021) argue that Arctic amplification should be attributed to the physical processes that establish the nonuniform vertical warming profile producing the lapse rate feedback, rather than the lapse rate feedback per se.

Given this debate, in this review, we focus on several of the key processes important to the ongoing discussion on Arctic amplification, focusing primarily on processes in the troposphere associated with blocking, moisture transport, and subseasonal influences. Our focus in the next sections is as follows: first, we review atmospheric blocking, including its definition, current challenges to identify present and future blocking, its relationship with moisture transport in the Arctic, and the impacts from Arctic blocking and moisture intrusions. We then review tropical-to-high latitude teleconnections that exert critical control on Arctic processes on the subseasonal time scale, both in the atmosphere and cryosphere. We conclude the review with a forward-looking assessment of how these interrelated topics are expected to evolve in future climate.

ARCTIC CIRCULATION FEATURES: BLOCKING, MOISTURE TRANSPORT, AND COUPLING WITH THE CRYOSPHERE

Blocking Definition, Identification, and Northern Hemisphere Climatology

Blocking is broadly defined as a quasi-stationary anomalous anticyclonic circulation pattern which disrupts the eastward propagation of cyclones and other systems (AMS American

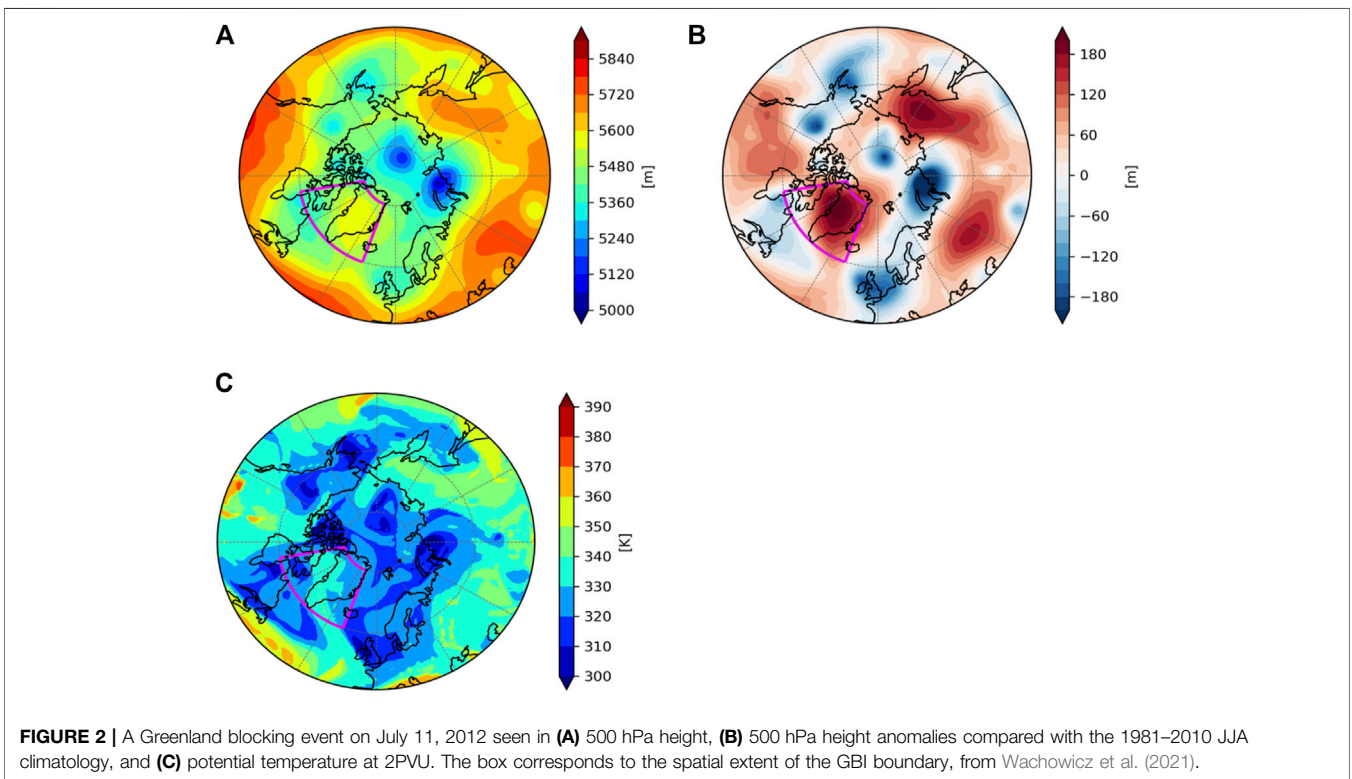
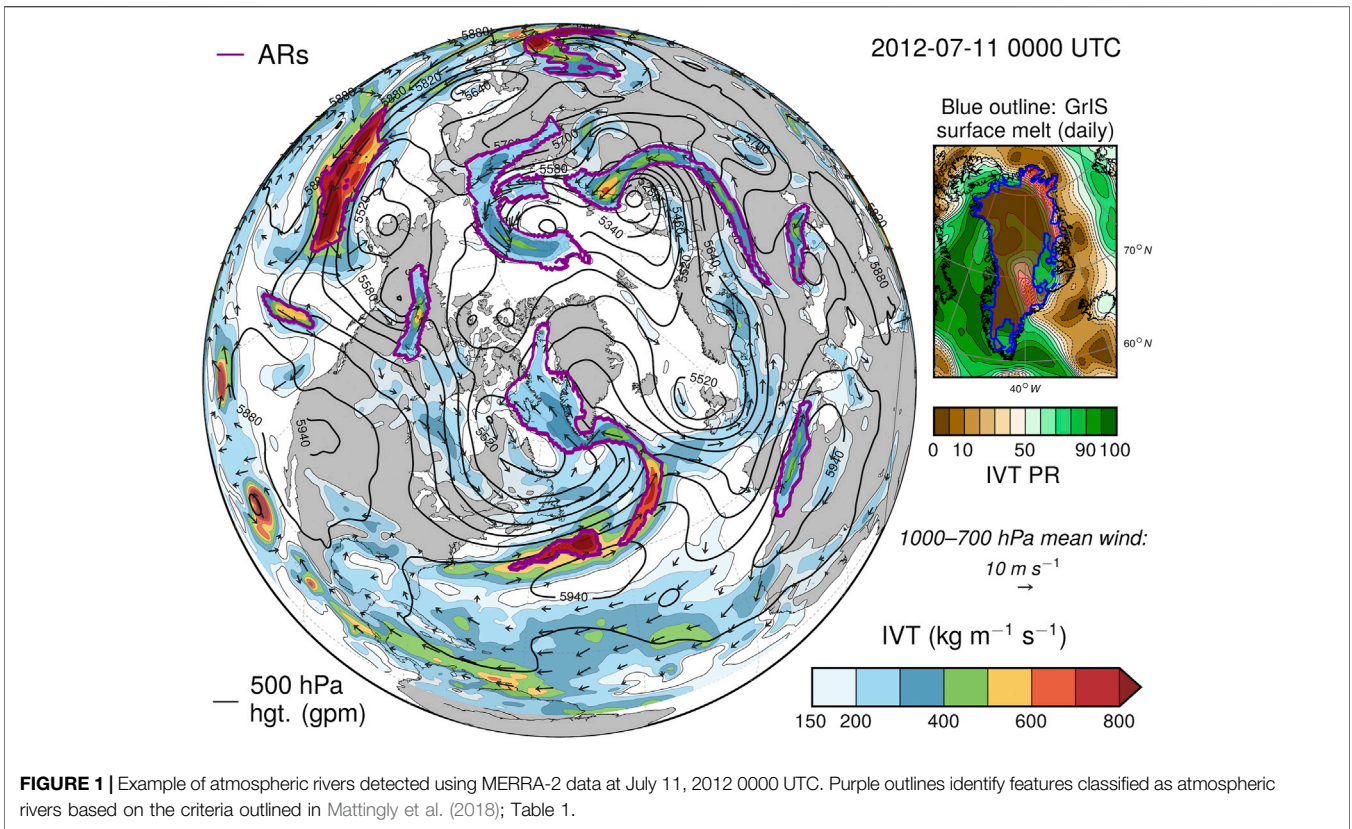
Meteorological Society, 2020). The formation of a blocking flow pattern results from disruption of the background flow interactions with Rossby wave dynamics (Woollings et al., 2018 and references therein). Mechanisms contributing to the building and maintenance of blocked systems can include moist-thermodynamic processes during cyclogenesis and transient eddies (e.g., Pfahl et al., 2015; Steinfeld and Pfahl, 2019). More recently, blocking has been described by the column budget of Local Wave Activity, using an analogy to traffic congestion (Nakamura and Huang 2018). Direct meteorological impacts of long-lived blocks vary seasonally, primarily resulting in extreme heat and cold airmasses (e.g., Brunner et al., 2018; Schaller et al., 2018), as well as increased advection of heat and moisture along the periphery of the anticyclones (e.g., Barrett et al., 2020; Mattingly et al., 2018) (Figure 1). In the high latitudes, environmental consequences can include significant loss of sea ice and ablation of land ice, as discussed in detail in *Tropical-High Latitude Subseasonal Teleconnections* (e.g., McLeod and Mote, 2016; Tedesco et al., 2016; Wernli and Papritz, 2018).

The broad definition of blocking has led to a variety of different methodological considerations for quantifying blocking and its impacts in the mid- and high-latitudes, particularly regarding spatial and temporal constraints and the dynamic considerations, as explained further in Woollings et al., 2018. The definition of atmospheric blocking has changed over time, resulting in a variety of different blocking identification methods used today. The earliest blocking detection studies, such as Rex (1950), defined blocking as a split jet over a 45° longitudinal span and persisting for 10 or more days. This definition was later revised to include shorter minimum durations, inclusion of latitudinal ranges, geopotential height anomaly thresholds, or a combination of these (e.g., Geb 1966; Charney et al., 1981; Treidl et al., 1981; Lejenas and Øakland, 1983). This has resulted in several papers highlighting advantages and disadvantages of differing methods (Barnes et al., 2012; Woollings et al., 2018; Wachowicz et al., 2021). While we do not intend to detail each separate metric available nor provide an exhaustive list, we briefly discuss some metrics below.

Geopotential Height-Based Indices

Geopotential height-based blocking identification methods are most common, given that geopotential height data is almost universally available in atmospheric reanalysis products and climate model intercomparisons. Consequently, metrics measuring the reversal of the 500-hPa height gradient (e.g., Lejenas and Øakland, 1983; Tibaldi and Molteni, 1990) are most common (Figure 2A). These methods use a constant reference latitude (e.g., 60° N) about which the gradient is computed (Tibaldi and Molteni, 1990), but these approaches may mischaracterize blocking in some regions (Pelly and Hoskins, 2003; Dunn-Sigouin and Son, 2013).

Other height-based metrics calculate regional average geopotential height, such as the Greenland Blocking Index (GBI) (Figure 2B) (e.g., Fang 2004; Hanna et al., 2014; Hanna et al., 2016) and Alaska Blocking Index (McLeod et al., 2018), where positive regional anomalies typically indicate blocking



conditions. While computationally straightforward, this anomaly type of method may be sensitive to long-term increases in geopotential heights due to climate change (Christidis and Stott, 2015), and may require detrending of the height field prior to calculation (Hanna et al., 2018a; Wachowicz et al., 2021). Similarly, the method described in Dunn-Sigouin and Son, 2013—based on methods from Barriopedro et al. (2010) and Dole and Gordon (1983)—calculates and tracks geopotential height anomalies, which reduces errors in blocking classification that occur when using a constant, reference latitude. Both height reversal and anomaly methods have various spatial, temporal, and amplitude constraints that vary by study, particularly regarding what constitutes instantaneous, regional, and sector blocking events and episodes (e.g., Tibaldi and Molteni, 1990; Dunn-Sigouin and Son, 2013).

PV- Θ -Based Indices

Methods employing a potential vorticity-potential temperature (PV- Θ) approach, which generally follow from Pelly and Hoskins (2003), identify instances of a reversal in the meridional potential temperature (Θ) gradient on a constant PV surface (Figure 2C). An advantage to these methods stems from theory in that Θ is conserved in the absence of diabatic processes (Hoskins et al., 1985; Hoskins 1997). These methods (e.g., Pelly and Hoskins, 2003; Tyrlis and Hoskins, 2008) consider the climatology of annual transient eddy kinetic energy (TEKE) in establishing a reference latitude, which varies with longitude. Moreover, the use of seasonal TEKE may better identify blocking in some regions (Tyrlis and Hoskins, 2008; Masato, et al., 2012; Wachowicz et al., 2021). This method has been adapted to examine Rossby wave breaking characteristics from blocking (e.g., Masato et al., 2012; Masato et al., 2013a; Woollings et al., 2018).

Despite their theoretical advantages, shortcomings of these methodologies include primarily the lack of isentropic variables, primarily in global climate model (GCM) output. As a consequence, others have been able to successfully apply somewhat similar techniques to 500-hPa data to examine blocking in these datasets (e.g., Barnes et al., 2012; Barnes, et al., 2014; Masato et al., 2013b; Simpson et al., 2020). Barnes et al. (2012) report that there is systematically little difference in blocking representation in climate models when comparing the methods, including Tibaldi and Molteni (1990) and Pelly and Hoskins (2003).

While the geographical distribution and frequency of blocking may vary depending on the blocking metric used, some common themes do emerge. Broadly, blocking activity is greatest along the climatological storm tracks—e.g., over the North Atlantic and Pacific Basins or over Asia (Lejenas and Øakland, 1983; Tibaldi and Molteni, 1990; Pelly and Hoskins, 2003). Depending on the method used, blocking occurs over preferred regions including Greenland, Europe, the Central Arctic, Ural-Siberia, and the North Pacific (e.g., Barnes et al., 2014; Horton et al., 2015; Woollings et al., 2018). Furthermore, application of these metrics typically shows blocking to be most common in winter and early spring and least common in summer due to climatological cyclone frequency (Woollings et al., 2018; Lupo 2020).

Stationary and transient eddies within Rossby waves increase poleward moisture and heat transport, and act to enhance upper-level ridges (Franzke et al., 2011; Baggett et al., 2016; Zhang and Wang, 2018; Steinfeld and Pfahl, 2019), leading to blocking conditions over a region (Kim and Kim, 2017; Yang and Magnusdottir, 2017). Rossby wave breaking and diabatic processes, such as latent heat release from moisture transport, can both play an effective role in generating and maintaining blocks (e.g., Masato et al., 2013a; Woollings et al., 2018; Luo et al., 2019; Steinfeld and Pfahl, 2019; Steinfeld et al., 2020). Though the average measured duration of blocking events is dependent on identification methodology, identification efforts indicate that individual blocking events typically last 4 to 9 or more days (Pelly and Hoskins, 2003; Tyrlis and Hoskins, 2008; Lupo et al., 2019). We direct the reader to Lupo (2020) for a more detailed description of specific climatological characteristics of Northern Hemisphere blocks. However, understanding high-latitude moisture transport pathways in more detail is required to fully quantify the impact of blocking within the Arctic climate system and these connections to Arctic amplification more broadly.

Arctic Moisture Transport Pathways and Climatology

The geographical setting of the Northern Hemisphere high latitudes—with oceanic “gateways” in the Atlantic and Pacific sectors opening to the partially confined Arctic Ocean basin, at the downstream terminus of major extratropical storm tracks—facilitates the coupling of Arctic climate with lower-latitude processes. One of the primary ways lower-latitude processes affect the Arctic is through direct poleward heat and moisture fluxes in the atmosphere, which act to partially offset the global radiative imbalance between the tropics and poles (Trenberth and Solomon, 1994; Overland et al., 1996). The major pathways for meridional sensible and latent energy transport into the Arctic are through the North Atlantic (including the Fram Strait and Barents-Kara seas to the east of Greenland and the Labrador Sea/Baffin Bay pathway to the west of Greenland), North Pacific, and Siberian sectors (Sorteberg and Walsh, 2008; Woods et al., 2013; Woods et al., 2017; Dufour et al., 2016; Vázquez et al., 2016; Xu et al., 2020; Mewes and Jacobi, 2019; Mewes and Jacobi, 2020). Most prior studies have focused on meridional moisture rather than sensible heat transport, and have found that moisture transport into the Arctic is greatest during summer and minimized during winter (Dufour et al., 2016). During winter (DJF), poleward moisture transport is mainly confined to the Barents-Kara seas and, to a lesser extent, the Labrador/Baffin Bay and North Pacific transport pathways (Naakka et al., 2019; Nygård et al., 2020). During summer (JJA), mean moisture transport is directed poleward through the North Pacific, Siberian, and Labrador/Baffin Bay pathways, with moisture transport in the North Atlantic sector tending to be diverted zonally over Eurasia and onward into the Siberian pathway (Naakka et al., 2019 - see their Figure 1). Spring (MAM) and autumn (SON) exhibit a mixture of winter and summer characteristics, likely because these averaging periods

capture transitions between the maximally frozen and thawed Arctic seasons (Tilina et al., 2014; Dufour et al., 2016).

Moisture transport into the Arctic does not occur in a temporally uniform manner, but rather is primarily accomplished through intense, short-lived events that are typically linked to cyclones (Sorteberg and Walsh, 2008; Dufour et al., 2016; Rinke et al., 2017; Villamil-Otero et al., 2018; Fearon et al., 2020) and Rossby wave breaking (Liu and Barnes, 2015). These events are often termed “moisture intrusions” (e.g., Doyle et al., 2011; Woods et al., 2013; Woods et al., 2017; Johansson et al., 2017; Yamanouchi, 2019; Ali and Pithan, 2020) and may resemble the narrow “atmospheric rivers” found in the mid-latitudes (Hegyi and Taylor, 2018; Komatsu et al., 2018; Nash et al., 2018; Vázquez et al., 2018).

Greenland Blocking: Impacts on Ice Sheet Surface Mass Balance and Relationships With Moisture Transport

Research efforts during the era of Arctic amplification have placed specific attention on atmospheric blocking and associated moisture transport over Greenland due to its impact on the surface mass balance (SMB) of the Greenland Ice Sheet (GrIS). Greenland blocking events encourage surface melt through a variety of mechanisms that will be discussed below and, as such, are strongly associated with increased GrIS surface melt and runoff over synoptic to decadal timescales (Hanna et al., 2013; Häkkinen et al., 2014; Hermann et al., 2020). This amplified runoff from the ice sheet can impact the climate system in several ways, including through contributions to global sea level rise. GrIS mass loss has contributed approximately 14 mm of sea level rise since the 1970s (Mouginot et al., 2019)—exceeding the upper end of estimates from GCM projections (Slater et al., 2020)—while continued runoff is expected to contribute from 5 to over 30 cm by the end of the century, and complete melt of the ice sheet would raise sea level by over 7 m (Aschwanden et al., 2019).

From a synoptic perspective, Greenland blocking events encourage melt by transporting moist, potentially warm air from unusually low latitudes poleward within the amplified ridge of the blocking anticyclone (Oltmanns et al., 2019; Steinfeld and Pfahl, 2019; Hermann et al., 2020), causing widespread, positive surface temperature anomalies across the ice sheet (Hanna et al., 2014; McLeod and Mote, 2016) (**Figure 2**). Advection from lower latitudes is greatest along the upstream side of the ridge. A common pattern involves southerly winds tracking the western coast of Greenland and curving anticyclonically to the north of the high-pressure center, transporting warm, moist air poleward through the Labrador Sea/Baffin Bay pathway (Baggett and Lee, 2019; Akers et al., 2020) described in *Arctic Moisture Transport Pathways and Climatology* (see **Figure 1**). This results in onshore flow over the ice sheet—a synoptic setting conducive to meltwater production (Mote, 1998b; Fettweis et al., 2011; Fettweis et al., 2013; McLeod and Mote, 2016). This transport of warm, moist air from lower latitudes along with the associated cloud cover anomalies produce widespread surface melt via a spatially varying surface energy balance (SEB) response (Cullather and Nowicki, 2018). However, this exact blocking

and moisture transport pattern is not observed during all major GrIS melt events, and the most recent such event in July 2019 involved an unusual blocking pattern transiting westward from Europe to Greenland (Cullather et al., 2020).

The strong advection of heat and moisture during Greenland blocking plays a crucial role in augmenting melt over the steep margins of the ice sheet by mixing warm, moist air to the surface from above the stable boundary layer that typifies the near surface atmosphere, thus enhancing sensible and latent heat flux and increasing the net SEB (Duynderke and van den Broeke, 1994; van den Broeke and Gallée, 1996; Mattingly et al., 2020). Turbulent heat flux associated with Greenland blocking has been shown to dominate the SEB response during intense melt across much of the ablation zone (Fausto et al., 2016a; Fausto et al., 2016b).

The cloud-radiative effects associated with Greenland blocking are reflective of the interaction between the large-scale synoptic setting and the topography of the ice sheet. As the flow is directed inland to the north of the high-pressure center, anomalously warm and moist air ascends the windward side of the ice sheet, cooling adiabatically (Hahn et al., 2020). This generates an increase in cloud cover and attendant downward longwave radiation while reducing incoming shortwave radiation over northern Greenland and higher elevations of the ice sheet (Hahn et al., 2020; Ward et al., 2020). Conversely, the southern part of the ice sheet is more frequently embedded within the ridge and, consequently, experiences cloud-suppressing subsidence that causes a reduction in downwelling longwave radiation and an increase in incoming shortwave radiation (Hofer et al., 2017; Noël et al., 2019; Hahn et al., 2020; Ward et al., 2020).

The importance of these cloud-radiative effects to the SEB varies geographically as dictated by surface albedo. In locations of high surface albedo, such as northern Greenland and the high-elevation accumulation zone, the SEB is resilient to changes in incoming shortwave radiation and, rather, longwave cloud-radiative effects dominate (Wang B. et al., 2018; Wang et al., 2019; Lenaerts et al., 2019 and references therein). In locations of lower surface albedo, such as southern Greenland and the low-elevation ablation zone, there is a greater sensitivity to changes in incoming shortwave radiation and, consequently, shortwave cloud-radiative effects dominate (Wang W. et al., 2018; Wang et al., 2019; Lenaerts et al., 2019 and references therein; Izeboud et al., 2020). This physical framework explains the seemingly disparate observational results showing that suppressed cloud cover over southern Greenland during frequent blocking events drives GrIS mass loss (Hofer et al., 2017) while also pointing to the critical role of moisture transport and the presence of low-level clouds in generating surface melt at high elevations during extensive melt events (Nghiem et al., 2012; Bennartz et al., 2013; Neff et al., 2014; Van Tricht et al., 2016; Gallagher et al., 2018; Tedesco and Fettweis, 2020).

The impact of each radiative term on the SEB is further complicated by the fact that the surface albedo of the ice sheet is not static with time. In what is referred to as the ice-albedo feedback, surface melt lowers albedo of ice sheet, first by accelerating snow metamorphism, then, in locations of seasonal snowpack, by uncovering lower-albedo glacial ice

(Tedesco et al., 2011; Box et al., 2012; Lenaerts et al., 2019 and references therein). Consequently, the influence of incoming shortwave radiation on the SEB increases following Greenland blocking onset (Tedesco et al., 2011; Tedesco et al., 2013; Tedesco et al., 2016) and the efficacy of shortwave cloud radiative effects is maximized at the heart of the melt season (Wang et al., 2019).

A related mechanism whereby Greenland blocking impacts the GrIS is by inhibiting snowfall that would otherwise act to increase both accumulation and surface albedo, thus driving below-normal SMB across portions of the ice sheet that are located within the ridge (Tedesco et al., 2011; Box et al., 2012; Tedesco and Fettweis, 2020). However, the anomalous moisture transport that accompanies Greenland blocking (e.g., Barrett et al., 2020; see also **Figure 1**) can also cause significant positive SMB anomalies in some situations. Mattingly et al. (2018) show that while strong moisture transport to western Greenland during the melt season is associated with increased melt in the ablation zone, these losses are partially compensated by snowfall in the accumulation zone, while anomalous moisture transport during non-summer months typically produces anomalous snowfall throughout the GrIS, especially in southeast Greenland. This demonstrates that the orientation of blocking anticyclones relative to the topography of the GrIS and their seasonal timing exert critical controls on SMB response.

Arctic Moisture Intrusions: Impacts on Sea Ice and Relationships With Blocking

Numerous studies have found that Arctic moisture intrusions cause sea ice melt or impeded growth. During the cold season, moisture intrusions trigger transitions from the “radiatively clear” to “opaquely cloudy” atmospheric states observed in Arctic field campaigns (Stramler et al., 2011; Woods and Caballero, 2016; Graham et al., 2017b; Cohen et al., 2017; Kayser et al., 2017; Ali and Pithan, 2020). Downwelling longwave radiation is enhanced by anomalous cloud cover and elevated water vapor amounts during subsequent days, which, along with the insulating effect of enhanced snow accumulation during the storms, reduces sea ice growth and may cause the sea ice edge to retreat (Park et al., 2015b; Merkouriadi et al., 2017; Merkouriadi et al., 2020; Persson et al., 2017; Graham et al., 2019). During summer, cyclones are less intense and the warming effect of moisture intrusions may be tempered by their associated negative shortwave cloud radiative effect, but episodes of warm, moist air advection have nevertheless been shown to force sea ice melt (Graversen et al., 2011; Rinke et al., 2019a), with case studies demonstrating the formation of a moist inversion and fog layer over sea ice that enhances downwelling longwave radiation and turbulent heat flux (Tjernström et al., 2015; Tjernström et al., 2019; You et al., 2020). Synoptic storms and moisture intrusions have been found to coincide with the initial melt of sea ice in early summer (Persson, 2012; Else et al., 2014; Hegyi and Deng, 2017) and the period of rapid warming during the Arctic springtime transition (Long and Robinson, 2017). Several studies have found correlations between enhanced winter and spring poleward moisture transport, increased longwave

radiation from cloud cover, earlier sea ice melt onset, and decreased sea ice cover during the subsequent September annual minimum (Kapsch et al., 2013; Kapsch et al., 2014; Kapsch et al., 2016; Kapsch et al., 2019; Park et al., 2015a; Cox et al., 2016; Mortin et al., 2016; Cao et al., 2017), although Choi et al. (2014) and Sedlar (2018) find that absorbed shortwave radiation absorption likely plays an important preconditioning role in spring and early summer as well. Winter and spring moisture intrusions are most frequent through the Atlantic sector of the Arctic (Yang and Magnusdottir, 2017; Messori et al., 2018; Hao et al., 2019; Hong et al., 2020; Papritz and Dunn-Sigouin, 2020).

The frequent recent occurrence of atmospheric blocking patterns alongside moist intrusions and warm extremes in the Atlantic and Pacific sectors shows that these circulation features are often closely related, and that blocking also influences sea ice evolution. Anticyclonic flow patterns over the Arctic have been linked to anomalously low summer minimum sea ice extent (Ogi and Wallace, 2012; Bellefamme et al., 2015; Ding et al., 2017; Wernli and Papritz, 2018; Rinke et al., 2019a), to extreme early sea ice melt in the Baffin Bay–Davis Strait–Labrador Sea sector in spring 2013 (Ballinger et al., 2018), and to negative sea ice extent anomalies around Alaska in all seasons (McLeod et al., 2018).

Several recent studies have detailed the complex circulation features and thermodynamic processes that produce episodes of extreme Arctic warmth, including interactions between cyclones, blocking, and moisture transport as well as the coupling between transport from lower latitudes and intra-Arctic thermodynamic processes. Papritz and Dunn-Sigouin (2020) analyzed a climatology of all extreme moisture transport events during winter, finding that planetary-scale anticyclones and synoptic-scale cyclones interact to produce the most extreme events, as blocks deflect the tracks of cyclones poleward and establish a strong poleward transport in the interaction zone between the block and upstream cyclones. During summer, Wernli and Papritz (2018) found that episodic upper-level Arctic anticyclones enhance sea ice reduction, and that extratropical cyclones injecting extratropical air masses with low potential vorticity into the Arctic are responsible for the formation of these anticyclones (in agreement with the extratropical-to-polar transport along moist isentropes described by Laliberté and Kushner (2014)). Binder et al. (2017) examined the dynamic and thermodynamic evolution of a winter 2015–16 extreme Arctic warm event in detail, finding that three air streams with distinct origins and warmed by different processes contributed to the warm episode: warm low-level air of subtropical origin, initially cold low-level air of polar origin heated by surface fluxes, and descending air heated by adiabatic compression. These airstreams were transported poleward by a low-level jet positioned between an anticyclone and a series of cyclones, with further warming by latent heating in a region of continuous warm conveyor belt ascent into the upper part of the anticyclone. Papritz (2020) extended this type of Lagrangian air mass evolution analysis to all Arctic lower-tropospheric warm (and cold) extreme events and found that blocking plays a critical role in generating warm extremes in both summer and winter. Subsidence from the Arctic middle

troposphere in blocking anticyclones was found to be the most important warming process, with anomalous blocking in the Barents, Kara, and Laptev Seas favoring warm extremes during winter and blocks located in the high Arctic during summer, when subsidence within blocks is particularly important for warming. Poleward transport of already warm air masses contributes around 20% to warming during both summer and winter, while about 40% of the air masses originate from the Arctic during winter and are heated diabatically by ocean-atmosphere fluxes in marine cold air outbreaks.

These recent studies expand upon and complicate the traditional view that cyclonic moisture intrusions directly transport already warm, moist air from lower latitudes to warm the Arctic and impact sea ice. It instead appears likely that lower latitude atmospheric processes contribute to Arctic warm events through complex planetary- and synoptic-scale dynamics that involve two-way interactions between the Arctic and lower latitudes in response to initial extratropical forcing, with critical contributions to final warming from intra-Arctic coupling between ocean and land surfaces, the atmospheric boundary layer, and the middle and upper troposphere. A further question concerns the vertical distribution of moisture transport in the Arctic atmosphere and its impact on amplification and near-surface warming. Corridors of direct moisture advection from the mid-latitudes to the Arctic tend to ascend from the surface to the middle troposphere along moist isentropes (Laliberté and Kushner, 2014; Wernli and Papritz, 2018; Hao et al., 2021), and Feldl et al. (2020) find that greater warming and moistening of the upper troposphere does not directly contribute to Arctic amplification as it does not affect the near-surface lapse rate feedback. However, transport of moist air masses from the mid-latitude near-surface layer to the Arctic middle and upper troposphere likely still contributes to Arctic warming indirectly, as latent heat release aids the formation of blocking anticyclones (Pfahl et al., 2015; Grams and Archambault, 2016; Zhang and Wang, 2018; Sánchez et al., 2020) that deflect cyclones poleward (Papritz and Dunn-Sigouin, 2020) and warm the lower troposphere through subsidence (Laliberté and Kushner, 2014; Ding et al., 2017; Wernli and Papritz, 2018; Papritz, 2020).

Further research is needed to clarify the complex interrelationships between cyclone-driven moisture intrusions, blocking, and sea ice in a rapidly changing Arctic, along with the contribution of these phenomena to overall Arctic amplification. These investigations should address the seasonality of cyclonic moisture intrusions and blocking and their role in Arctic warming, as Arctic-amplified warming is most pronounced during winter, while the warming contribution of subsidence within anticyclones is maximized during the summer according to Papritz (2020). Arctic blocking is less studied than in the mid-latitudes, and future studies should ensure that any blocking detection algorithms employed in this emerging area of research are suitable to detect Arctic blocks, which are generally weaker than their mid-latitude counterparts and may not be detected by geopotential height-based algorithms (see *Blocking Definition, Identification, and Northern Hemisphere Climatology*), that require poleward westerlies (Tyrlis et al., 2020). The vertical

structure of moisture transport should be carefully examined in relation to blocking and influences on warming, as Arctic moistening in lower levels likely contributes directly to the lapse rate feedback, while middle- and upper-tropospheric moisture transport may contribute to warming through more indirect pathways including latent heat release and blocking development, and/or may act to dampen Arctic amplification due to a negative upper-level lapse rate feedback (Feldl et al., 2020; Hao et al., 2021). The relative importance of and relationships between lower-latitude and within-Arctic processes during Arctic warming events should also be further investigated. Recent studies reviewed here show that a large proportion of air masses originate from within the Arctic during these warm events, but the thermodynamic processes occurring within local and remote air masses to produce warming are linked to extra-Arctic atmospheric circulation features, thus the interactions between variability in the extratropical storm tracks and Arctic circulation extremes are an important avenue for future research. These questions regarding local and remote drivers of episodes of anomalous Arctic warming mirror the broader debate over local and remote influences on Arctic amplification, and future research should assess the overall significance of remotely forced cyclonic moisture intrusions and blocking to Arctic-amplified warming, including their interactions with mechanisms that have traditionally been conceptualized as intra-Arctic processes such as the ice-albedo, lapse rate, and cloud and water vapor feedbacks.

TROPICAL-HIGH LATITUDE SUBSEASONAL TELECONNECTIONS

Intraseasonal Influences on Extratropical Rossby Waves

In order to understand the potential future evolution of high-latitude circulation and its association with Arctic amplification, it is critical to understand lower-latitude and tropical processes. Tropical upper-tropospheric heating produced by thunderstorms in the convectively active region of the leading mode of atmospheric subseasonal variability, the Madden-Julian Oscillation (MJO; Madden and Julian, 1971; Madden and Julian, 1972; Madden and Julian, 1994), has been found to be an effective source of Rossby wave generation to the extratropics and Arctic (Hoskins and Karoly, 1981; Sardeshmukh and Hoskins, 1988; Bladé and Hartmann, 1995; Jin and Hoskins, 1995; Hendon and Salby, 1996). To generate these Rossby waves, diabatic heating produced by MJO deep convection leads to a divergent component of the upper-tropospheric tropical and subtropical wind field. That divergent wind then advects absolute vorticity toward the poles and leads to the formation of a wave train (Kiladis and Weickmann, 1992; Knutson and Weickmann, 1987; Sardeshmukh and Hoskins, 1988; Hendon and Salby, 1994; Higgins and Mo, 1997; Matthews et al., 2004; L'Heureux and Higgins, 2008; Lin et al., 2009; Seo and Son, 2012; Riddle et al., 2013) that can be traced (Seo and Lee, 2017; Barrett, 2019). The Rossby wave train's subtropical origins depend on the

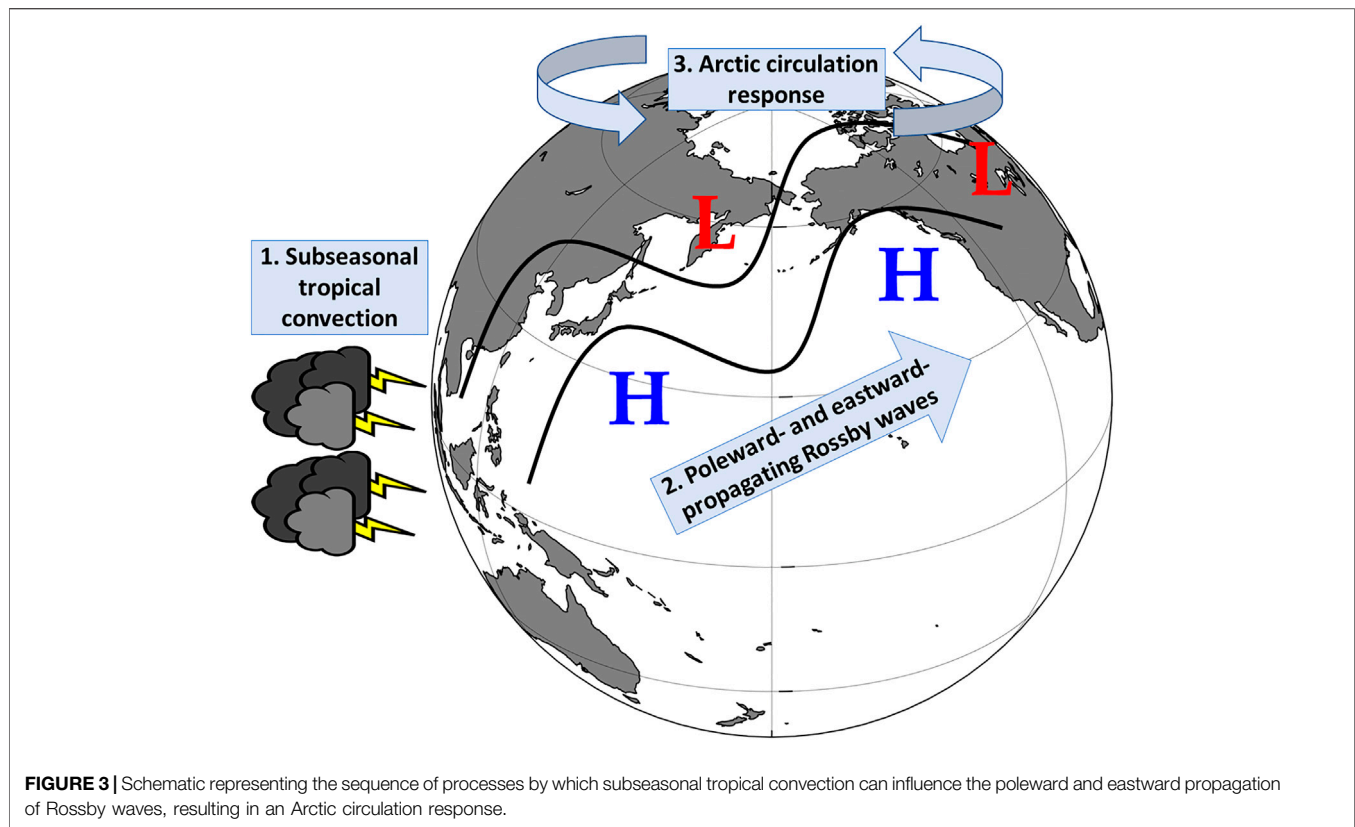


FIGURE 3 | Schematic representing the sequence of processes by which subseasonal tropical convection can influence the poleward and eastward propagation of Rossby waves, resulting in an Arctic circulation response.

longitude of the MJO convection, and the origin of the wave train can move east, in tandem with the diabatic heating source (Johnson and Feldstein, 2010; Hamill and Kiladis, 2014; Stan et al., 2017). The Rossby wave source region can extend across nearly the entire tropical Indian Ocean and the Pacific Ocean west of 180° (Lukens et al., 2017), and that allows the MJO to modulate tropical cyclones in the Atlantic Ocean (Barrett and Leslie, 2009). One proposed physical mechanism for Rossby wave generation is as follows: when the MJO convection is over the Indian Ocean, horizontal convergence in the tropics and the advection of absolute vorticity in the subtropics develops a cyclonic anomaly over southeast Asia. As MJO convection moves eastward, a Rossby wave train departs the subtropics in the exit region of the subtropical Pacific jet (Lukens et al., 2017). Another proposed physical mechanism for Rossby wave generation involves modulation of the local Walker and Hadley cell circulations (Schwendike et al., 2014) over the Pacific. The subtropical jet over the Pacific is enhanced in regions of anomalous upper-tropospheric (anticyclonic; Roundy, 2012) divergence located poleward of MJO convection (Matthews and Kiladis, 1999; Moore et al., 2010). This jet shifts eastward with the MJO propagation, and regions of enhanced convection strengthen the local Hadley circulation, and as upper-tropospheric flow accelerates poleward due to pressure gradient forces, geostrophic adjustments yield troughing downstream of ridging, thereby producing midlatitude Rossby waves that propagate poleward across the Pacific Ocean in both the

Northern and Southern Hemispheres (Schwendike et al., 2021).

Because of this important influence, predicting the future state of high-latitude circulation, precipitation, temperature, and cryosphere (snow and ice) depends on the correctly capturing the temporal evolution and geographical distribution of tropical convection of the MJO (Jones et al., 2004; Marshall et al., 2011; Riddle et al., 2013; Rodney et al., 2013; Goss and Feldstein, 2015; Tseng et al., 2018; Lin and Brunet, 2018; Zheng et al., 2019; Zheng and Chang, 2019; Zheng and Chang, 2020; Tseng et al., 2020). Indeed, the broader topic of polar amplification of surface temperature and precipitation has been linked to poleward-propagating Rossby waves excited by MJO-related tropical convection (Figure 3) (Lee et al., 2011). Furthermore, there is evidence that many of the blocked atmospheric circulations in the Arctic that were reviewed in *Blocking Definition, Identification, and Northern Hemisphere Climatology* are have connections to tropical convection on the subseasonal time scale (Henderson et al., 2016; Henderson and Maloney 2018), and even the moisture pathways and atmospheric rivers reviewed in *Blocking Definition, Identification, and Northern Hemisphere Climatology* and *Arctic Moisture Intrusions: Impacts on Sea Ice and Relationships With Blocking* may also have connections to the MJO on the subseasonal time scale (Mundhenk et al., 2016).

It remains an open question whether the extratropical Rossby wave train depends more on characteristics of the source region or either the tropical or extratropical flow (Roundy, 2021). Regardless, the Rossby wave response seems to be strongest

when the MJO diabatic heating structure resembles a dipole but with asymmetries that are not yet fully understood (Lin and Brunet, 2018). Moreover, stronger MJO events do not necessarily produce stronger extratropical responses or in the same location as weaker MJO events (Lafleur et al., 2015). Another uncertainty comes in the timing of the lagged response, with studies suggesting the lag can be anywhere from 1 to 3 weeks (Higgins et al., 2000; Lin and Brunet, 2009; Riddle et al., 2013; Rodney et al., 2013; Schreck et al., 2013; Matsueda and Takaya, 2015; Seo et al., 2016; Hu et al., 2019).

Approximately 30% of the variability of the subseasonal upper-tropospheric extratropical circulation can be linked with MJO-induced teleconnections (**Figure 3**) (Matthews et al., 2004; Seo and Son, 2012; Seo et al., 2016). One of the critical consequences of the diabatic heating of the MJO is that it is able to produce long-lasting responses in the high latitudes that last much longer than their tropical forcing (Matthews et al., 2004; Kim et al., 2006; Branstator, 2014; Franzke et al., 2019). This suggests the low-frequency evolution of the MJO in the future will affect many of the processes responsible for Arctic amplification. One other important open question regarding MJO-linked Rossby waves centers on seasonality. There is much research that suggests the MJO is strongest in extended boreal winter (November–May; see reviews by Zhang, 2005 and Zhang et al., 2013). However, in extended boreal summer months (June–September), the tropical intraseasonal oscillation exhibits multiple propagation characteristics: east and north over the Indian monsoon region (Murakami and Nakazawa, 1985; Hartmann and Michelsen, 1989; Gadgil and Srinivasan, 1990) and northwest over the western North Pacific Ocean (Murakami, 1980; Lau and Chan, 1986; Chen and Murakami, 1988). This change in propagation has led to the MJO being referred to as the boreal summer intraseasonal oscillation (BSISO; Krishnamurti and Subrahmanyam, 1982; Yasunari, 1979). The ability of the BSISO to act as a Rossby wave source into the midlatitudes remains significantly understudied when compared to the MJO (Wang et al., 2020a; Wang et al., 2020b). Thus, studies of Arctic amplification in summer months should also consider the teleconnected influence from the BSISO in the tropics, just as studies of Arctic amplification in winter should consider the influence from the tropical MJO.

Despite the remaining questions on the seasonality and strength of the MJO-driven Rossby wave trains, it is very clear that the MJO modulates a wide range of weather phenomena located in the tropics, the mid-latitudes and even in the high latitudes.

Subseasonal Influence on Mid-to-High Latitude Circulation and Surface Variables

In addition to the Rossby wave pathways discussed in *Intraseasonal Influences on Extratropical Rossby Waves*, another primary way by which the MJO influences surface variables is by strongly modulating the extratropical North Atlantic Oscillation (NAO) and Pacific–North American (PNA) pattern. The PNA and NAO are two of the leading modes of Northern Hemisphere extratropical variability

(Blackmon et al., 1984; Hurrell et al., 2001). Over the Pacific, the PNA pattern has been found to be related to the MJO. The MJO's modulation of the PNA pattern is caused by two Rossby wave sources: a negative source north of MJO-enhanced convection over the Indian Ocean and a positive source north of the MJO-enhanced convection over the western Pacific Ocean (Seo and Lee, 2017). When the MJO convection is in the Pacific Ocean, it tends to excite the positive PNA phase, which translates into above-normal geopotential heights over western North America, below-normal heights over eastern North America (Higgins and Mo, 1997; Mori and Watanabe, 2008; Franzke et al., 2011), and colder-than-normal temperatures over the northeastern United States (Leathers et al., 1991).

Flatau and Kim (2013) noted that the MJO forces the annular modes (the AO and NAO) on intraseasonal time scales. The MJO and NAO have a statistically significant time-lagged relationship. Between 7 and 10 days after MJO convection is over the Indian Ocean (phases 2–3), the probability of a positive NAO is increased significantly from the background climatology. Similarly, between 7 and 10 days after MJO convection is over the western Pacific Ocean (phases 6–7), the probability of a negative NAO is increased significantly (Cassou, 2008; Lin et al., 2009; Yadav and Straus, 2017). This pathway, called by Barnes et al. (2019) the “tropospheric pathway”, is one way that the MJO can influence the NAO. Another mechanism is via the polar stratosphere, and that is not reviewed here, beyond noting that the tropospheric pathway may depend on the prevailing direction of tropical stratospheric winds of the quasi-biennial oscillation (QBO) (when QBO is westerly, the MJO-NAO tropospheric pathway is more robust; Barnes et al., 2019; Feng and Lin, 2019). A positive NAO is associated with anomalous ridging over the eastern United States and North Atlantic Ocean and thus with warmer surface air temperatures and less precipitation (Hurrell et al., 2001; Hurrell et al., 2003). Conversely, a negative NAO is associated with anomalous troughing over the eastern United States and North Atlantic Ocean and thus colder surface air temperatures and more precipitation. Thus, above-average surface temperatures and below-normal precipitation can be expected over the eastern United States after MJO convection is over the Indian Ocean. Similarly, colder temperatures and above-normal precipitation can be expected after MJO convection is over the western Pacific Ocean.

The MJO's impacts on surface weather can be explained by the extratropical circulation anomalies forced by the tropical MJO convection (**Figure 3**). Zheng et al. (2018) noted that impacts on extratropical sea-level pressure, and thereby cyclone activity, may be greatest over the eastern North Pacific, the southeastern United States, Canada, and the north-central Atlantic Ocean. Temperature impacts, however, could be more significant over the eastern U.S. (Zheng and Chan, 2019). The anomalies in pressure and temperature have been definitively linked to the Rossby wave trains excited by the MJO, given that the upper-tropospheric circulation anomalies are equivalent barotropic (Zheng and Chan, 2019), thereby allowing any enhancement or suppression of the wind field to cause temperature advection. Zheng and Chan (2019) conclude: “the upper-level Rossby wave

train is very important as it connects the MJO and extratropical surface weather anomalies.”

One of the most important ways in which the MJO's influence extends to the Northern Hemisphere high latitudes is via its influence on surface air temperature (Lin and Brunet 2009; Yao et al., 2011; Yoo et al., 2011; Yoo et al., 2012; Zhou et al., 2012; Rodney et al., 2013; Johnson et al., 2014; Yoo et al., 2014; Lin 2015; Oliver 2015) and precipitation (Bond and Vecchi 2003; Jeong et al., 2008; Lin et al., 2010; Becker et al., 2011; He et al., 2011; Baxter et al., 2014; Jones and Carvalho 2014). Vecchi and Bond (2004) found that geopotential height, specific humidity, and surface air temperature in the Arctic varied by phase of the MJO, while Lin and Brunet (2009) confirmed a similar response of surface air temperature in Canada. Modulation of the Arctic atmosphere specifically, by phase of MJO has also been documented (L'Heureux and Higgins 2008; Yoo et al., 2011), while Yoo et al. (2012) further confirmed the MJO-driven, poleward propagating wave train drove changes in the Arctic overturning circulation, heat flux, and downward infrared radiation. Barrett et al. (2015), Klotzbach et al. (2016), Henderson et al. (2017), and Barrett (2019) noted that the MJO's influence on circulation and temperature extends to snowfall, and that for the eastern parts of North America, snowfall, snow depth change, and snow water equivalent change all tended to be above normal (or snowier) after MJO convection in phases 8 and 1. This relationship between the MJO and NAO appears to be strongest when the El Niño–Southern Oscillation (ENSO) is in negative (La Niña) phase (Roundy et al., 2010), and as discussed above, when the stratospheric QBO is in its easterly phase (Yoo and Son, 2016).

In addition to documented relationships between MJO and high-latitude temperature and precipitation tendencies via modulation of large-scale circulation, the MJO's influence has already been found to extend to Arctic sea ice (Henderson et al., 2014), by projecting onto the Arctic atmosphere in both boreal winter and summer seasons. Indeed, sea ice concentration is lower in both the Barents and Kara Seas one to two weeks after convection over the Maritime Continent, as a result of stationary wave interference and subsequent Arctic warming (Goss et al., 2016). Variability in sea ice concentration by phase of MJO was supported by corresponding lower troposphere atmospheric anomalies, with evidence of sea ice modulation occurring regionally. Daily changes in Northern Hemisphere (NH) spring snow depth by phase of MJO was explored by Barrett et al. (2015), with statistically significant depth anomalies found in March, April and May for both North America and Eurasia. In October, correlations between patterns of snow water equivalent (SWE) variability over Eurasia and mid-tropospheric geopotential heights were largest during MJO phases 4–7, indicating that tropical convection anomalies over the Indian Ocean and Maritime continent had the most impact on October circulation and snow variability (Henderson et al., 2017). These studies therefore provide additional evidence for connections between the tropics and the extratropics on subseasonal timescales.

FUTURE IMPLICATIONS FOR BLOCKING, MOISTURE TRANSPORT, SUBSEASONAL VARIABILITY, AND ARCTIC AMPLIFICATION

Arctic Amplification & Northern Hemisphere Blocking

There are several working hypotheses for how Arctic Amplification may influence mid-latitude weather extremes, and we refer the reader to existing reviews of the subject for a more thorough examination of the mechanisms behind both winter (Cohen et al., 2014; Cohen et al., 2020) and summer (Coumou et al., 2018) circulation response to Arctic change. Here, we briefly summarize some of these theoretical frameworks as they pertain to blocking. One prominent hypothesis to explain changes in mid-to high-latitude atmospheric circulation follows from the observation that Arctic amplification weakens the near-surface meridional temperature gradient, thus reducing the strength of the jet stream aloft (Francis and Vavrus, 2012; Francis and Vavrus, 2015; Cvijanovic and Caldeira, 2015; Deser et al., 2015; Vavrus et al., 2017). It is proposed that, under a weaker jet, Rossby waves become more amplified, and their westward progression slows, creating conditions that are conducive to blocking (Francis and Vavrus, 2012). It has also been argued that changes in snow cover or sea ice extent can exert an influence on blocking by altering the stationary wave pattern, thus bringing the background state of the atmosphere in certain regions closer to blocked conditions (Matsumura and Yamazaki, 2011; Wu et al., 2013; Cohen et al., 2014; Kim et al., 2014; Nakamura and Huang, 2018). Regarding winter circulation response, research efforts have also placed focus on a stratospheric pathway, where reduced sea ice along the Siberian coast may work in concert with increased snow cover over Eurasia in fall to elicit an increase in the upward propagation of Rossby waves that then disrupts the stratospheric polar vortex and exerts a downward influence on the troposphere, causing a negative AO by late winter (Cohen et al., 2007; Kim et al., 2014; Sun et al., 2015; McKenna et al., 2018; Henderson et al., 2018; Siew et al., 2020). This is relevant to blocking as the negative AO is associated with increased blocking throughout the Northern Hemisphere (Thompson and Wallace, 1998; Hassanzadeh and Kuang, 2015). In summer, it is thought that the enhanced thermal contrast between land and ocean under Arctic amplification increases the formation of wave guides that can encourage wave-amplifying resonance between free and forced Rossby waves, in turn promoting high-amplitude, persistent weather patterns such as those associated with atmospheric blocking (Coumou et al., 2018 and references therein).

Observed and Projected Trends in Northern Hemisphere Blocking, the Greenland Ice Sheet, and Poleward Moisture Transport

Documenting observational support of the theoretical linkages between Arctic amplification and blocking outlined above is an active area of research. While there is no current consensus about

observed trends in overall Northern Hemisphere blocking (Woollings et al., 2018), regional trends have been documented despite differences among both blocking metrics and datasets (Barnes et al., 2014).

An analysis of Local Wave Activity has suggested increases in such activity correspond to increases in blocking (Martineau et al., 2017), where cyclonic events are most influential for the development of high-latitude blocks (e.g., Woollings et al., 2018). Martineau et al. (2017) show an increase in local wave amplitudes (i.e., waviness) over East Asia, noting, however, trends in teleconnections such as El Niño/Southern Oscillation (ENSO), the Arctic Oscillation (AO)/North Atlantic Oscillation (NAO), and Pacific-North American teleconnections (PNA) may explain this connection (e.g., Cohen et al., 2012; Kosaka and Xie 2013). In particular, the negative phase of the AO/NAO is associated with both an increased frequency and higher latitude of blocking highs throughout the Northern Hemisphere (Thompson and Wallace, 1998; Hassanzadeh and Kuang, 2015).

Belleflamme et al. (2015) and Ballinger et al. (2014) show that increased anticyclonic activity over the Beaufort Sea and Greenland regions from 1980–2014 may have both contributed to and been the result of Arctic sea ice loss. In particular, the period of 2007–2012 experienced significant anticyclonic circulation anomalies in these regions, which cannot be attributed to either natural climate variability or anthropogenic climate change (Belleflamme et al., 2015; Ballinger et al., 2014; and references therein). In their review paper, Woollings et al. (2018) indicate historical increases in JJA blocking, depending on the metric used, particularly over Greenland and the North Atlantic as well as the Bering Sea during the 1958–2012 period.

GCMs included in the Coupled Model Intercomparison Project phase 3 (CMIP3) and phase 5 (CMIP5) intercomparisons have suggested an overall decrease in blocking frequency in response to climate change in the Northern Hemisphere (e.g., Barnes et al., 2012; Dunn-Sigouin and Son, 2013; Matsueda and Endo, 2017). Most CMIP5 models qualitatively simulate the blocking climatology locations, but underestimate blocking frequency under the RCP8.5 scenario (Dunn-Sigouin and Son, 2013). However, the trends appear to vary both regionally and seasonally. Kennedy et al. (2016) show a decrease in blocking over Eurasia, which is consistent with findings from other studies (e.g., Masato et al., 2013a; Hanna et al., 2018a); Woollings et al., 2018. Under the RCP8.5 scenario, there will likely be a decrease in blocking frequency in both the North Atlantic and North Pacific in fall and winter (Dunn-Sigouin and Son, 2013). Dunn-Sigouin and Son (2013) also show an increase in Ural blocking in future scenarios, although this result is not robust, as described in Woollings et al. (2018). Interestingly, they suggest an increase in European blocking. Additionally, the spatial extent of blocking events is expected to increase, where this increase is greatest for summer blocking (Nabizadeh et al., 2019).

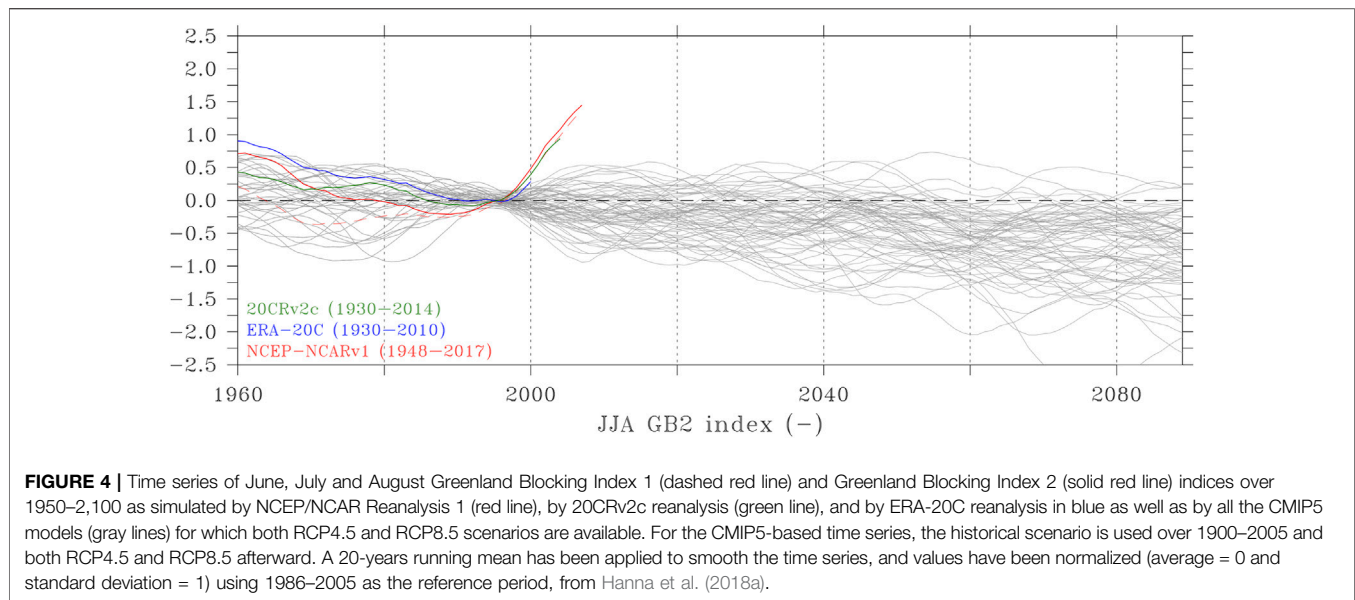
More recently, there has been significant improvement in blocking representation from CMIP5 to CMIP6, though the extent of this improvement still remains dependent on individual models, selected blocking metrics, regions, and

seasons (e.g., Davini and D'Andrea, 2020; Schiemann et al., 2020; Simpson et al., 2020). For example, Simpson et al. (2020), Supplementary Information report that overall CMIP6 models appear to better represent the observed spatial climatology compared to CMIP5 although systematic biases in the mean climate state maybe the cause of readily apparent underestimation of wintertime European blocks, and under-(over-)estimation of summer Ural (Eastern Russia) blocking frequency. Similarly, Davini and D'Andrea (2020) confirm the improved overall representation compared to CMIP3. Current CMIP6 projections suggest an overall decrease in blocking more generally in winter and summer, with possible increases in the (summer) Ural and (winter) western North American blocking (Davini and D'Andrea, 2020). Schiemann et al. (2020) report that the regional CMIP6 blocking bias magnitude is sensitive to the blocking metric used.

Given the impact on GrIS SMB, there is a clear motivation to understand long-term variability in Greenland blocking frequency. On an interannual basis, blocking frequency over Greenland has been shown to be strongly related to the North Atlantic Oscillation (NAO). The frequency of blocking highs over Greenland is greater when the NAO is in its negative phase, i.e., when the difference between its two pressure centers, the Azores and Iceland, is minimized (Hanna et al., 2014; Hanna et al., 2015; Hanna et al., 2018a; Hofer et al., 2017). As such, both the NAO and Greenland blocking have been linked to GrIS melt variability, with the latter explaining more of the variance in surface melt (Mote, 1998a; Hanna et al., 2013; McLeod and Mote, 2016).

A growing body of work has highlighted an increase in summer Greenland blocking over the past 2 decades, particularly as measured by the GBI (e.g., Hanna et al., 2016; Hanna et al., 2018a; Hanna et al., 2018b; McLeod and Mote, 2016; Barrett et al., 2020; Wachowicz et al., 2021). Wachowicz et al. (2021) confirmed this summer increase using a 5-years running mean of blocking frequency as measured using both geopotential-height-reversal-based and potential-vorticity-based blocking indices. As one might expect given relationship outlined above, this increase in blocking frequency has coincided with a period of a more negative NAO conditions (Fettweis et al., 2013; van Angelen et al., 2014; Bevis et al., 2019), all of which has occurred against a backdrop of dramatic sea ice and snow cover loss (Derksen and Brown, 2012; Cohen et al., 2014; Pithan and Mauritsen, 2014; Stroeve and Notz, 2018). The coincident nature of these events has spurred interest in the possibility that the change in circulation may be a feature of arctic amplification.

Several studies have invoked either declining sea ice or snow cover as a potential explanation for anomalous anticyclonic conditions over Greenland. A collection of modeling and observational studies has demonstrated anomalous anticyclonic conditions over Greenland in years of low sea ice extent (Screen, 2013; Wu et al., 2013; Petrie et al., 2015; Liu et al., 2016), suggesting the additional heat flux from the ice-free ocean may act to enforce the ridge aloft. Supporting this theory, Wu et al. (2013) tied the summer circulation response to sea ice in the seas west of Greenland by tracking a stationary wave that originates at the surface in spring then persists into summer.



Alternatively, Overland et al. (2012) pointed to the observed decline in Northern Hemisphere snow cover extent as a potential explanation for a recent shift in Arctic circulation that features positive pressure anomalies spanning the Arctic coastline of North America, including all of Greenland. Later work demonstrated a possible physical mechanism for this theory where low spring Eurasian snow cover extent increases the poleward propagation of Rossby waves which acts to decelerate the polar jet and encourage a negative AO (Matsumura et al., 2014)—conditions that are associated with increased blocking frequency (Thompson and Wallace, 1998; Hanna et al., 2014; Hanna et al., 2015; Hanna et al., 2018b; Hassanzadeh and Kuang, 2015).

Collectively, GCMs from CMIP3 through CMIP6 have consistently projected a decline in North Atlantic blocking in both winter and summer under future climate scenarios (Davini and D’Andrea, 2020; Masato et al., 2013b; Hanna et al., 2018a). However, GCMs generally fail to adequately represent blocking frequency and duration (Vial and Osborn, 2012; Woollings et al., 2018) and, critically, historical GCM simulations fail to capture the recent positive trend in summertime Greenland blocking, undermining confidence in projections of future blocking in this region (Davini and D’Andrea, 2020; Hanna et al., 2018a) (Figure 4). This underrepresentation carries significant implications, as accurate representation of regional circulation over Greenland is essential for GrIS SMB projections. Indeed, underestimation of GrIS SMB loss is a primary contributor to the negative bias in GCM projections of sea-level rise to date (Slater et al., 2020). Furthermore, a recent idealized modeling analysis found that a continuation of the recent increase in Greenland blocking would cause SMB losses to be more than twice than what is currently estimated from GCM projections (Delhasse et al., 2018).

An increasing trend in episodes of warm and moist air intrusion into the Arctic has been observed. Several episodes

of extreme winter warmth have extended latitudinally to the North Pole in recent years (Park D. S. R. et al., 2015; Cullather et al., 2016; Moore, 2016; Lee H. J. et al., 2017; Graham et al., 2017a; Binder et al., 2017; Kim et al., 2017; Kohnemann et al., 2017), and southerly winds contributed to the appearance of anomalous polynya north of Greenland during February–March and August–September 2018 (Moore et al., 2018; Ludwig et al., 2019; Lei et al., 2020). These extreme warm events are often coupled to Ural and Scandinavian blocking patterns (Luo et al., 2017; Rinke et al., 2017; Luo et al., 2019), and their frequent recurrence in recent winters may be linked to the increased incursion of warm, salty Atlantic Water—known as “Atlantification”—in the Atlantic sector of the Arctic Ocean (Alexeev et al., 2017; Polyakov et al., 2017; Polyakov et al., 2020a; Polyakov et al., 2020b; Barton et al., 2018; Tsubouchi et al., 2021). Dramatic sea ice decline and ocean warming have also been observed in the Pacific sector of the Arctic during recent years, alongside persistent atmospheric blocking and southerly moisture intrusions (Lee S. et al., 2017; Overland et al., 2018; Ballinger et al., 2019; Tachibana et al., 2019; Polyakov et al., 2020a; Huntington et al., 2020; Kodaira et al., 2020; Thoman et al., 2020).

Model simulations of future climate states indicate that poleward moisture transport into the Arctic will increase in the future, while dry static energy transport will decrease due to a decreased temperature gradient between the Arctic and lower latitudes (Hwang et al., 2011; Yoshimori et al., 2014b; Yoshimori et al., 2017; Graverson and Burtu, 2016; Feldl et al., 2017; Feldl et al., 2020; Graverson and Langen, 2019). In general, increased poleward water vapor flux can be expected to contribute to amplified Arctic warming through the greenhouse effect of water vapor and clouds as well as latent heat release from condensation. However, recent studies reviewed in *Arctic Circulation Features: Blocking, Moisture Transport, and Coupling With the Cryosphere* suggest that the warming

impact of increasing moisture flux will not be spatially and temporally uniform, and will depend on the vertical structure of water vapor transport as well as its interaction with the atmospheric circulation. Further, changes in water vapor transport from outside the Arctic will likely interact in complex ways with changing within-Arctic hydroclimatological conditions resulting from sea ice loss and ocean warming. The influence of declining sea ice on cyclones, moisture transport, and blocking, and in turn the feedbacks of these atmospheric processes into sea ice and oceanic conditions, should be studied further. For example, Kim and Kim (2017) hypothesized that the increasing open water fraction from sea ice decline will reduce the ocean-atmosphere temperature gradient and suppress turbulent heat flux into the atmosphere, which will serve to slow Arctic warming and enhance the role of atmospheric heat and moisture transport from lower latitudes in Arctic climate.

Future Trends in Tropical-To-Arctic Teleconnections

High-latitude atmospheric circulation is strongly influenced by lower-latitude processes, including those from the tropical and subtropical Pacific, through the poleward propagation of Rossby wave trains (e.g., Ding et al., 2014; Feng et al., 2017; Jiménez-Esteve and Domeisen, 2018). In order to understand the potential future evolution of the high-latitude circulation and its association with Arctic amplification, it is necessary to understand the future evolution of those lower-latitude processes. Some studies suggest that recent Arctic amplification could be at least partially attributed to enhanced warm-air advection and moisture transport by Rossby waves associated with an increase in the frequency of MJO activity over the western Pacific and Maritime Continent (Lee et al., 2011; Yoo et al., 2011; Yoo et al., 2012; Seo et al., 2016; Jiang et al., 2020). However, there are more studies that examine changes in the MJO (both historical and future) than changes in MJO-driven teleconnections to the high latitudes. Here, we review aspects of both changes to the MJO and its teleconnections.

The MJO is strongly influenced by the atmospheric mean state in the tropics (Maloney and Hartmann, 2001; Inness and Slingo, 2003; Zhang and Dong, 2004; Maloney and Xie, 2013). Thus, changes in tropical sea-surface temperatures, wind shear, moisture availability, and stability driven by anthropogenic global warming all have the potential to influence the MJO, and by association, Arctic amplification. Some studies suggest that the amplitude of the MJO may intensify and its variance increase with increasing warming (Takahashi et al., 2011; Liu et al., 2013; Schubert et al., 2013; Subramanian et al., 2014; Arnold et al., 2015; Wolding et al., 2017; Haertel, 2018; Rushley et al., 2019). Others suggest the MJO may become spatially more expansive in the zonal direction, with greater surface convergence, enhanced deep convection, faster eastward propagation, and more heating (Caballero and Huber, 2010; Arnold et al., 2013; Liu, 2013; Liu et al., 2013; Chang et al., 2015; Song and Seo, 2016; Adames et al., 2017; Cui and Li 2019). While most studies suggest a more intense MJO over the 21st

century, some suggest that an increase in tropical static stability may weaken the MJO's generation of Rossby waves (Bui and Maloney, 2018; Bui and Maloney, 2019a) by weakening the wind response. This weakening would have important implications for Arctic amplification, since the divergent flow anomalies produced by the MJO's anomalous heating are the source for Rossby wave generation into the extratropics (Sardeshmukh and Hoskins, 1988; Wolding et al., 2017; Maloney et al., 2019). Some modeling results suggest that teleconnected impacts in the Arctic may be weaker per unit of MJO precipitation anomaly over the next several decades (Jiang et al., 2020). This is further complicated because the MJO-Arctic link depends strongly on complex, nonlinear changes in extratropical static stability, storm track, North Pacific jet stream, and other aspects of the general circulation that all impact the receivership state of the Arctic to MJO teleconnections (Kang and Tziperman, 2018; Bui and Maloney, 2019b; Jiang et al., 2020).

Given all this, many questions remain unanswered regarding the role of tropical teleconnections and their impact on Arctic amplification. The extent to which MJO can influence atmospheric blocking is relatively understudied; however, preliminary work suggests that not only does MJO affect blocking frequency in particular at higher latitudes (Henderson et al., 2016), the relationship is also influenced by ENSO phase (Henderson et al., 2018). Future implications of this tropical-to-Arctic Amplification linkage are further complicated as studies disagree on projections of increased MJO precipitation under warmer climates (e.g., Schubert et al., 2013; Rushley et al., 2019). Moreover, few studies have examined either MJO teleconnections, in general, or MJO-Arctic linkages in warmer climates (e.g., Maloney et al., 2019; Jiang et al., 2020). More research is needed to fully understand the complex, multi-layered and non-linear processes that connect tropical and extratropical atmospheric circulation, its interaction with atmospheric blocking and moisture transport, and subsequent impacts on and amplification of changing Arctic atmospheric and surface variables.

Summary and Discussion

Arctic amplification is a fundamental feature of past, present, and modeled future climate. However, the causes of this amplification within Earth's climate system are not fully understood. To date, warming in the Arctic has been most pronounced in autumn and winter seasons, with this trend predicted to continue based on model projections of future climate. The intra-Arctic feedbacks by which this is taking place are numerous and interconnected, while extra-Arctic processes, in particular changes to large-scale atmospheric circulation and moisture transport, are entangled with these internal feedbacks in complex ways.

A question we pose is whether external forcing from the tropics is appropriately considered in a discussion of Arctic amplification. If one defines Arctic amplification in a manner in which the Arctic specifies both the region in which the enhanced warming is observed and also all feedbacks involving amplification occur, then consideration of tropical forcing would fall outside the discussion. However, if we broaden the discussion to include mechanisms that import

sensible and latent heat into the Arctic and thereby enhance local longwave forcing, in addition to mechanisms that modulate Arctic atmospheric circulation, triggering within-Arctic feedbacks (e.g., ice-albedo, lapse rate), then inclusion of forcing from lower latitudes becomes critical. We therefore have reviewed forcings acting within and external to the Arctic that lead to enhanced warming and cryospheric impacts in this region.

We have anchored our discussion of Arctic atmospheric circulation features on atmospheric blocking and moisture transport, as these phenomena have been widely studied and are interrelated mechanisms by which lower-latitude processes can couple with high-latitude Arctic climate. Blocking can broadly be defined as a quasi-stationary anomalous anticyclonic circulation pattern which disrupts the eastward propagation of cyclones and other systems, analogous to traffic congestion within the atmosphere (Nakamura and Huang, 2018). Poleward moisture transport into the Arctic is primarily accomplished by short-lived intrusion events associated with cyclones, which preferentially occur in certain regions and seasons as detailed in *Arctic Moisture Transport Pathways and Climatology*. Blocking and moisture transport are closely related, as poleward moisture transport is favored along the upstream flank of a blocking anticyclone, and latent heat release within the moisture plume often helps maintain or strengthen the block. These phenomena have important regional and global climate implications due to their influence on Greenland Ice Sheet surface mass balance and Arctic sea ice variability (*Greenland Blocking: Impacts on Ice Sheet Surface Mass Balance and Relationships With Moisture Transport and Arctic Moisture Intrusions: Impacts on Sea Ice and Relationships With Blocking*). Greenland blocking and episodes of extreme moisture transport into the Atlantic and Pacific sectors of the Arctic have shown increasing trends in recent years, highlighting the importance of further research to clarify the complex interrelationship between cyclone-driven moisture intrusions, blocking, and sea and land ice in a rapidly changing Arctic, along with the contribution of these phenomena to overall Arctic amplification.

With the nature of these Arctic moisture intrusions being associated with short-lived, intense events linked to cyclones (Sorteberg and Walsh, 2008; Dufour et al., 2016; Rinke et al., 2017; Villamil-Otero et al., 2018; Fearon et al., 2020) and Rossby wave breaking (Liu and Barnes, 2015), we have also reviewed the role of tropical subseasonal atmospheric variability in forcing extratropical and polar atmospheric circulation (*Tropical-High Latitude Subseasonal Teleconnections*). The MJO has been found to be an effective source of Rossby wave generation to the extratropics (Hoskins and Karoly, 1981; Sardeshmukh and Hoskins, 1988; Bladé and Hartmann 1995; Jin and Hoskins, 1995; Hendon and Salby, 1996), with poleward-propagating Rossby waves excited by MJO-related tropical convection being linked to polar amplification of surface air temperature (Lin and Brunet, 2009; Lee et al., 2011; Yao et al., 2011; Yoo et al., 2011; Yoo et al., 2012; Zhou et al., 2012; Rodney et al., 2013; Johnson et al., 2014; Yoo et al., 2014; Lin, 2015; Oliver, 2015), precipitation (Bond and Vecchi, 2003; Jeong et al., 2008; Lin et al., 2010; Becker et al., 2011; He et al., 2011; Baxter et al., 2014; Jones

and Carvalho 2014), sea-level pressure, snow depth (Barrett et al., 2015; Henderson et al., 2017), and sea ice (Henderson et al., 2014).

Although our focus in this review is on subseasonal extra-Arctic forcing originating in the tropical Pacific and Indian Oceans, we also note that a number of studies have shown that Atlantic Ocean variability can influence Northern Hemisphere high latitude climate on interannual to multidecadal time scales (e.g., Kwon and Joyce, 2013; Hahn et al., 2018; Kwon et al., 2018; Kwon et al., 2020; Joyce et al., 2019; Athanasiadis et al., 2020). Future studies should examine the relative importance and characteristic time scales of these Indo-Pacific and Atlantic influences on Arctic climate in a coherent framework.

When considering future Arctic climate, a great deal of uncertainty exists due to rapid, and in some cases unprecedented, changes that have already occurred in recent decades. Here, we have focused on within- and extra-Arctic process drivers, specifically high-latitude atmospheric blocking, poleward moisture transport, and tropical-high latitude subseasonal teleconnections, and the role they have on the Arctic atmosphere, surface variables and amplification of changes in this region. Remaining questions arise from 1) the theoretical linkages between Arctic amplification and blocking, 2) the future evolution of poleward moist and dry static energy transport, and 3) future change in tropical subseasonal variability. Observed blocking trends are dependent on the metrics used to quantify such events and there are inconsistencies in current climate models' abilities to fully capture blocking. Poleward moisture transport is projected to increase in a warming climate, but the vertical structure of moisture transport will likely determine the magnitude of its contribution to Arctic surface warming (*Arctic Moisture Intrusions: Impacts on Sea Ice and Relationships With Blocking*), and decreasing dry static energy transport due to sea ice loss may limit increases in total atmospheric heat transport to the Arctic (Audette et al., 2021). Similarly, divergent consensus on future trends of tropical subseasonal variability under a warmer climate makes projections of MJO-Arctic linkages under such climates challenging, and warrants more research to understand this complex and highly non-linear connection between the tropics and Arctic amplification.

AUTHOR CONTRIBUTIONS

GH outlined the study scope, which was then further developed by all authors. Additionally, she co-led *Intraseasonal Influences on Extratropical Rossby Waves, Subseasonal Influence on Mid-to-High Latitude Circulation and Surface Variables*, and *Future Trends in Tropical-To-Arctic Teleconnections* with BB, and led *Summary and Discussion*. Additionally, Barrett produced the **Figure 3** schematic. KM outlined *Arctic Circulation Features: Blocking, Moisture Transport, and Coupling With the Cryosphere* with LW and JP, and led the writing of *Arctic Moisture Transport Pathways and Climatology, Arctic Moisture Intrusions: Impacts on Sea Ice and Relationships With Blocking* and *Observed and Projected*

Trends in Northern Hemisphere Blocking, the Greenland Ice Sheet, and Poleward Moisture Transport. LW and JP led the writing on *Blocking Definition, Identification, and Northern Hemisphere Climatology, Greenland Blocking: Impacts on Ice Sheet Surface Mass Balance and Relationships With Moisture Transport* and *Arctic Amplification & Northern Hemisphere Blocking*. TM helped frame the paper, and contributed to *Summary and Discussion*.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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