CHAPTER

15

The jet stream and climate change

Martin Stendel[1], *Jennifer Francis*[2], *Rachel White*[3],
Paul D. Williams[4], *Tim Woollings*[5]

[1]Department of Climate and Arctic Research, Danish Meteorological Institute, Copenhagen, Denmark; [2]Woodwell Climate Research Center, Falmouth, MA, United States; [3]Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC, Canada; [4]Department of Meteorology, University of Reading, Reading, United Kingdom; [5]Department of Physics, University of Oxford, Oxford, United Kingdom

1. Introduction

1.1 Jet streams

The jet streams are powerful, relatively narrow currents of air that encircle the globe from west to east in both the northern and southern hemispheres. While the strongest winds are found at heights of 10—15 km, typical of cruising aircraft, jet streams, particularly in temperate latitudes, "steer" the movement of frontal zones and air masses, thus affecting surface weather and contributing to the prevailing westerly winds familiar to many in the mid-latitude regions.

The jet streams rose to prominence in meteorology following World War II, when high-altitude air campaigns had on several occasions been adversely affected by unexpectedly strong winds [1]. The establishment of hemispheric-scale networks of radiosonde observations by Carl-Gustav Rossby and collaborators in the 1940s and 1950s identified for the first time the global nature of the jet streams and the waves that propagate along them [2]. Since then, the jets have been central to our understanding of weather patterns and climate variability.

Although not observed or measured until relatively recently, the existence of jet streams was theorized by George Hadley in the 18th century in his groundbreaking discussion on the cause of the tropical trade winds [3]. Hadley correctly identified the rotation of the Earth and the nonuniform distribution of solar heating as the two key ingredients needed to explain the trade winds. As hot air rises above the equator, relatively cool air is pushed along the surface from both Northern and Southern Hemispheres to replace it. Conservation of

Climate Change, *Third Edition*
https://doi.org/10.1016/B978-0-12-821575-3.00015-3

momentum implies that these air masses must turn westward over the Earth's surface as they approach the equator, as their distance from Earth's rotation axis increases. Hence, the easterly trade winds are born. High up at the top of Hadley's circulation cell, he predicted that air moving poleward must similarly acquire velocity from west to east. In meteorology, such currents are termed “westerly” winds, i.e., winds *from* the west.

Momentum transport associated with the tropical Hadley cells is hence a key process responsible for driving the subtropical jet streams. However, in midlatitudes,[1] the atmosphere is dominated not by planetary cells such as Hadley's but by abundant turbulent and chaotic eddy circulations known collectively as the “storm tracks.” These eddies crucially also act to accelerate the westerly jet streams and are increasingly viewed as blending seamlessly with the tropical circulation in achieving the poleward energy and momentum transport required of the atmosphere, since the tropical regions receive more energy from the Sun than the polar regions, and temperature differences between the tropics and the poles cannot grow indefinitely. Cartoons of the atmosphere often indicate two separated jets in each hemisphere: a subtropical jet located at the edge of the Hadley cell and a subpolar jet at higher latitude. In reality, the latitude of the jets varies with both longitude and time, and the subtropical and subpolar jets are often merged into one band of strong westerly winds in the midlatitudes, known generally as the jet streams.

In the absence of surface asymmetries and large-scale instability, the jets would uniformly encircle the globe, but regional features—such as continents, mountain ranges, and patterns of ocean temperatures—act to shape the regional jet streams by forcing north–south wave patterns known as Rossby waves (or planetary waves). These waves are named for Carl-Gustaf Rossby who first developed, during the 1930s, the theory of these flow patterns in fluids such as the atmosphere (or ocean) on rotating planets. These regional features can also explain why a strong and straight jet is observed across the North Pacific, while the jet is more variable over the North Atlantic [4,5]. We thus often refer to individual jets, for example, as the North Pacific jet or the North Atlantic jet.

1.2 Jet streams and Rossby waves

The radiosonde networks spearheaded by Rossby in the 1930s–40s were crucial for identifying not just the hemispheric jet stream but also the planetary-scale waves that now bear his name (Fig. 15.1). Rossby waves are pervasive features of any large-scale weather map and, in some sense, are more fundamental features of the atmosphere than even the jets themselves. These waves manifest as trains of alternating weather patterns—low pressure, high pressure, low pressure, and so on—generally arranged in a line roughly from west to east. These pressure anomalies are known, respectively, as ***cyclones*** (low pressure) and ***anticyclones*** (high pressure). If a jet stream is present, then the waves can be seen as meanders in the jet, as it snakes to the north and south of the weather systems.

Rossby waves arise from the conservation of vorticity, or informally “spin,” in geophysical fluid dynamics. Vorticity comprises two components, one due to the rotation of air masses *relative* to the Earth's surface and one due to the *planetary* rotation of the Earth itself.

---

[1] The region between the tropics and the polar circles (Tropic of Cancer and Arctic Circle on the Northern and Tropic of Capricorn and Antarctic Circle on the Southern Hemisphere).

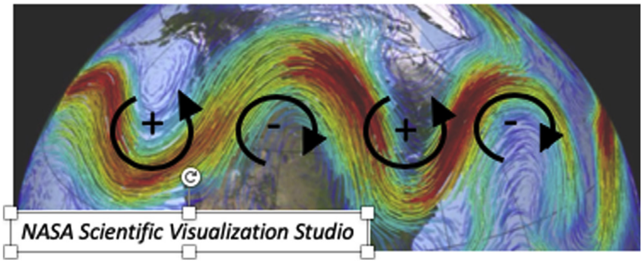

FIGURE 15.1 A view of the subpolar jet stream (colored wavy streamlines depicting the wind speed, with dark red colors depicting the fastest winds) with an example of a Rossby wave in the Northern Hemisphere. Rossby waves lead to positive ("+") and negative ("−") vorticity anomalies that form cyclones and anticyclones, respectively. For further discussion, see text. *Figure adapted from an image by the NASA Scientific Visualization Studio.*

If an air mass moves poleward, for example, its planetary vorticity will increase because its local vertical axis is aligned more closely with the axis of the Earth. Its relative vorticity therefore has to decrease to compensate, so it spins relative to the ground in the opposite direction to the Earth, forming an anticyclone. The essence of Rossby waves is that neighboring air masses affect each other and can grow and propagate as waves of vorticity anomalies (e.g., Ref. [6]).

Rossby waves are thought to play a central role in the formation of jet streams in general. On large, planetary scales (on the order of 5000 km), the atmosphere behaves in many ways like a two-dimensional fluid, with stirring introduced by the growth of vortices (eddies) in the unstable midlatitude regions. This growth, termed ***baroclinic instability***, arises because of the strong meridional (north/south) temperature gradient in the mid-latitudes. The instability arises because cold, dense air sits alongside warm, lighter air. In such a setting, two-dimensional turbulence theory predicts that eddies should merge and grow to ever larger length scales. However, the planetary rotation critically constrains the flow: As the eddies grow, the efficiency of Rossby wave propagation increases until the wavelike parts of the flow dominate, and the disturbances propagate away as Rossby waves. The waves tend to ultimately propagate out of the midlatitude band, toward both the north and south, and the structure of the waves in this situation acts to transport westerly momentum back into the central region of the jet where the eddies grew. Hence, the "eddy-driven" jets are formed, without the need for an adjacent Hadley cell. These jets are common features of our oceans and the atmospheres of other planets as well as our own [7,8].

In the absence of background winds, Rossby waves would propagate toward the west; however, the westerly winds typical of the midlatitudes blow, or "advect," the anticyclonic (clockwise) and cyclonic (counterclockwise) vorticity anomalies of the Rossby wave toward the east. When these two processes balance, i.e., the westward Rossby wave propagation is equal to the eastward advection by the westerly winds, a ***transient*** (propagating) wave becomes ***stationary***. This is described physically as the wave having zero phase speed, where the phase speed describes how fast the individual peaks and troughs of a wave propagate relative to the Earth. Such Rossby waves typically exist on weather timescales (days to weeks), and thus, we use the term ***quasi-stationary*** to distinguish these waves from the ***stationary waves*** that are present when taking a time average over many years for a particular season. These stationary waves are largely forced by land—sea contrasts and mountain ranges (see, e.g. Ref. [4]) and typically have a larger spatial scale than quasi-stationary or transient waves. Quasi-stationary waves are of particular importance for persistent weather and weather extremes, as we will see in the next section.

The speed of Rossby wave propagation depends on the spatial scale of the wave, such that larger Rossby waves travel toward the east more slowly than smaller Rossby waves. This means that the strength of the zonal wind required to make a wave stationary also depends on the spatial scale of the wave [9]. As the zonal wind speed varies with time, latitude, and longitude, the spatial scale of the quasi-stationary waves will also vary. Thus, if there are changes in the average strength, latitude, or variability of the jets with a warming climate, the average spatial scale of quasi-stationary and stationary waves will be affected (see Section 2.2).

An exact definition of quasi-stationary waves has yet to be agreed upon in the literature, but relevant studies typically look at waves present in data averaged over 2 weeks to 1 month (e.g., Refs. [10,11,12]) or use quasi-stationary to refer to relatively short waves with near-zero phase speed [10]. Linear Rossby wave theory, together with observations of some events, suggests that at least some long-lasting quasi-stationary wave events are not just one singular wave but rather are recurrent Rossby wave events, in which a series of transient, propagating waves all have phases that line up, such as in Fig. 15.2 [11].

In addition to shifting, pulsing, and stationary waves, a distinct form of jet variability is associated with a process termed ***atmospheric blocking*** (e.g., Ref. [13]). This typically involves the local and temporary deflection of the jet and associated storm track by a large-scale, persistent weather pattern, often involving a stationary anticyclone. Blocks typically last for a week or two, and this persistence can lead to severe weather impacts that often enhance seasonal contrasts, discussed further in Section 1.4.

The interaction between jets, Rossby waves, and blocking is complex and remains a topic of active research. While the jets, particularly outside of the subtropics, generally owe their existence to the propagation of Rossby waves, the waves themselves are often strongly affected by the jets. Analysis of jet stream characteristics by Woollings et al. [14] supports the association of weaker jet stream winds with increased occurrences of blocks

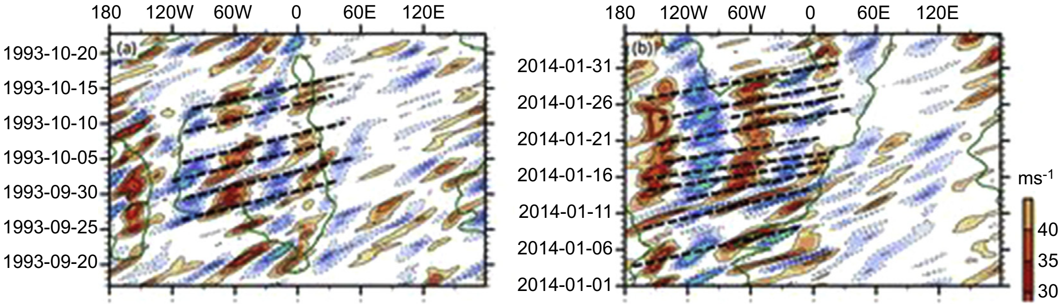

FIGURE 15.2 Hovmoller plots showing 250-hPa meridional wind averaged between 35° and 65°N during two separate recurrent Rossby wave events. *Black dashed lines* highlight the individual wave packets. Note that each wave packet is propagating in space; however, the phase alignment of successive packages results in a quasi-stationary signal. Here, hPa refers to hectopascals or hPa.

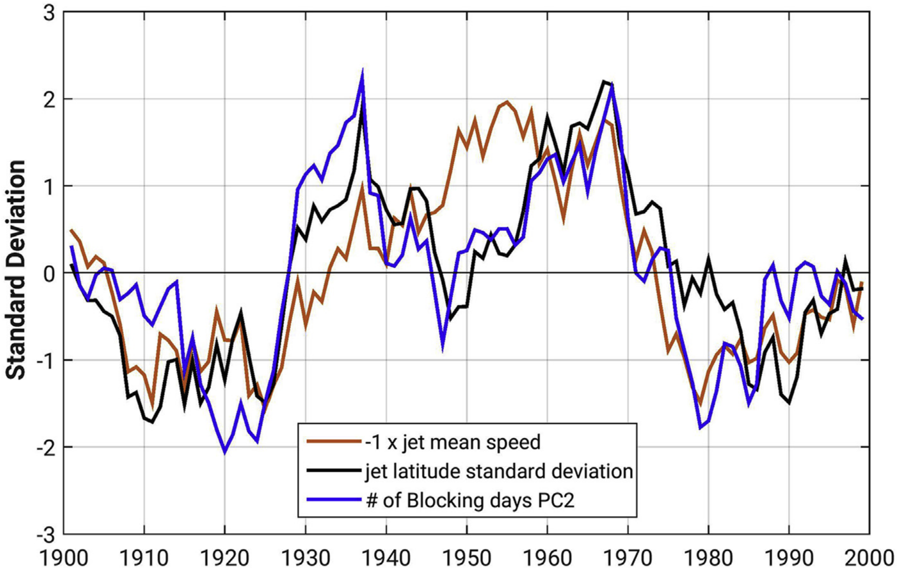

FIGURE 15.3 Time series of North Atlantic winter blocking and jet diagnostics from the 20CR reanalysis. All series have been smoothed with an 11-yr running mean. *From [14].*

(eddies in the flow) and a larger variance in jet stream latitude, which can be interpreted as increased waviness (Fig. 15.3). Similarly, Blackport and Screen [15] show that weaker equator to pole surface temperature gradients, associated with weaker jets, leads to a "wavier" circulation (as measured by local wave activity), and vice versa, on interannual to decadal timescales. Interestingly, they did not find this relationship to hold for longer-term changes, i.e., with anthropogenic climate change; this will be discussed further in Section 2.2.

A jet stream manifests as a concentrated gradient of vorticity, so that the jet locally enhances the background poleward gradient of vorticity owing to the rotation of the Earth. This gradient in vorticity is exactly where Rossby waves grow and propagate, and idealized wave theories suggest that Rossby waves should bend toward strong and narrow jet streams. Indeed, in certain circumstances, jets can act as ***atmospheric waveguides*** that locally trap the waves in a narrow band of latitudes [16,17].

As noted earlier, the distribution of land and mountains on Earth creates zonal asymmetries in jet strength, which in turn creates zonal asymmetries in the atmospheric waveguides [16]. This is illustrated in Fig. 15.4, depicting the climatological mean zonal wind in the upper troposphere (the troposphere is the layer of atmosphere from the surface to an altitude of approximately 14 km) in boreal summer (June−August) in black contours (highlighting the jets), and the frequency of the presence of a local waveguide in colored shading. Zonal variations in the waveguides create variations in waves properties at different longitudes, with more zonal propagation in regions with stronger waveguides [18,19].

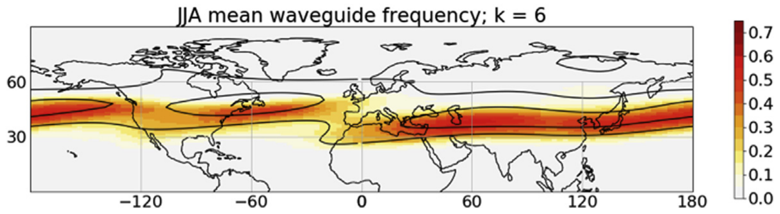

FIGURE 15.4 *Black contours* showing the Northern Hemisphere midlatitude upper troposphere (300 mb) jet (zonal wind; black lines, contour interval 10 m/s) in boreal summer. Shading shows the frequency of waveguide occurrence for wavenumber k = 6. See Ref. [20] for details on the waveguide detection.

1.3 Natural variability of the jet streams

Jet streams, in particular those with a strong eddy-driven component, are highly variable in terms of position and strength, and these variations give rise to many regional weather and climate impacts. Atmospheric variability has historically been described using fixed spatial anomaly patterns, deriving from a correlation or principal component analysis[2] (see, e.g., Ref. [21]). The dominant patterns, often termed annular modes or oscillations, as in the North Atlantic Oscillation (NAO), generally reflect changes in the latitudinal position and/or strength of the jet stream [22,23,24]. The dominance of these structures attests to the power of the jets in influencing climate: Across much of the Earth's surface, the single most important piece of information for regional climate is the strength and relative position of the jet.

Much jet variability can be conceptually viewed as a pulsing in strength or shifting in latitude of jet streams, such as those in the North Atlantic and Pacific sectors of the Northern Hemisphere, although other factors such as the meridional tilt of a jet can also be important (e.g., Ref. [25]).

The jets can vary naturally on timescales from weeks to decades in a complex interaction of timescales [26]. While much of this variability was previously thought to be chaotic in origin [27], recent work has shown that a considerable part of the variability in seasonal mean jet states is in fact predictable a season or more beforehand [28]. These findings have refocused attention on predictable drivers of jet variability, in particular via stationary Rossby waves forced by tropical variability [29]. Tropical variability has long been understood as a key driver of jet variability, with El Niño/Southern Oscillation (ENSO) events standing as the classic example, but subseasonal variations such as the Madden-Julian Oscillation have also been shown to exert similar influence on jet variability from week to week in the midlatitudes [30].

Atmospheric blocks are connected with jet variability, as they typically involve a blocking, or diversion, of the jet around the blocked region. Blocks are very diverse in their configurations and mechanisms, with complex interactions often occurring between blockings and Rossby waves [31]. The amplification and breaking of Rossby waves are often crucial for blocking occurrence [32,33,34], and some, but certainly not all, blocking anticyclones can

---

[2] A method of multivariate statistics used to approximate a large data set with a small number of linear combinations of variables retaining as much as possible information from the original data.

be considered part of a larger quasi-stationary Rossby wave. Research is still ongoing to fully understand the dynamics of blocking events. One recently suggested approach proposes an analogy between atmospheric blocks and the dynamics of traffic jams [35]. The idea is to assign a "capacity" of air to the jet streams, just like the capacity of a motorway. When this capacity is exceeded, the flow is blocked, similar to a traffic jam, and it is suggested that both blocking and traffic jams can be described by the same mathematical model. It is yet to be seen if this analogy holds up to further scrutiny.

1.4 The jet stream, Rossby waves, and weather

Variability in the jet streams and associated Rossby waves play a critical role in our weather and climate. Numerous extreme weather and climate events can be attributed to jet stream variability, to name just a few examples: the cold European winter associated with a southward jet shift in 2010 [36], the hot European summer associated with a northward jet shift in 2018 [37], and the prolonged California drought of 2011–17, linked to a northward displaced jet [38].

As shown in Ref. [39], a variety of extreme weather events—such as heatwaves, cold spells, and stormy periods—are more likely when high-amplitude Rossby waves are present (often thought of as when the jet stream is in a relatively wavy state). Large waves span many degrees of latitude, allowing atmospheric disturbances traveling along the jet stream to tap into tropical heat and moisture more effectively, fueling storm development, transporting heat far poleward, and increasing the likelihood of heavy precipitation. In the Northern Hemisphere, deep southern excursions of the jet stream can usher Arctic air into regions unaccustomed to freezing temperatures and generate strong east–west temperature gradients that are essential ingredients for snowstorms. In addition, the anticyclones in the Rossby waves are typically associated with clear skies and thus hotter weather in summer. Thus, large waves are associated with both hot extremes [40] and cold extremes [41]. Moreover, as large waves tend to progress eastward more slowly, this can cause weather regimes to stall and create persistent conditions that may lead to extreme events.

Indeed, many precipitation and temperature extreme events have been associated with high-amplitude Rossby waves in both winter and summer [42,43,10,44,39]. This includes, for example, the persistent cold spells in winter 2009/2010 in Europe and the winter of 2013/2014 in the eastern United States, as well as the European heatwaves of 2003 and 2018 and the Russian heatwave and Pakistan floods of 2010. The circulation anomalies associated with the waves lead to regions of northerly (winds from the north) and southerly (winds from the south) air flow. Where the winds flow from equator to pole, they bring hot and often humid air; conversely, they bring cold dry air to regions where they flow in the opposite direction.

Rossby waves are also associated with the transport of moisture, as well as with a phenomenon known as ***atmospheric rivers*** [45,46]. Atmospheric rivers are narrow bands of extremely moist air reaching from the tropics (where the atmosphere is typically more humid) into the midlatitudes and sometimes even farther poleward. They transport large amounts of moisture and so are often associated with extreme precipitation events [47]. As examples, Rossby waves have been linked to precipitation extremes including the Pakistan floods of 2010 and Balkan floods of 2014 [48,49].

In addition to causing extreme events in a single region, some Rossby waves can extend zonally (west to east) for long distances [18]; the simultaneous occurrence of several such large-scale waves with a particularly high amplitude can lead to concurrent extreme events in disparate regions of the Earth, with the potential even to affect global crop yields [50]. Such zonally extensive Rossby waves across a continent, along with other aspects of high-amplitude Rossby waves, have been connected with atmospheric waveguides trapping Rossby wave activity in a confined latitude band.

Atmospheric blocking events (introduced in the previous section) also influence weather by obstructing the mild westerly flow into the continents. Through the same arguments as given earlier for the impact of Rossby waves on circulation and thus temperature, blocks can lead to both extreme cold days in winter and extreme hot days in summer, although there are differences in the mechanisms in the different seasons [51,52].

Much of the theory and connections discussed earlier apply to all seasons; however, atmospheric circulation, as well as the dynamics of extremes, change substantially with the seasons, and so it is often instructive to explore some aspects of the influence of jets and Rossby waves on weather separately for the cold versus warm seasons.

1.4.1 *Autumn/winter*

Under the right conditions, wave energy from the tropospheric jet stream can be transmitted upward into the stratosphere (the stably stratified atmospheric layer above the troposphere, in which temperature generally increases with height). If enough energy is transferred over a week or more, the usually fairly circular stratospheric polar vortex (SPV; a strong cyclone normally located over the North Pole in the stratosphere, leading to a strong stratospheric jet around 60N, present during the cold season) can be disrupted: It can shift away from the pole, become elongated, or even split into two or more subvortices. These events are called sudden stratospheric warmings and are particularly important as, despite occurring high up in the atmosphere, they can have a strong influence on our weather at the surface [53]. When these events occur, pools of frigid Arctic air can penetrate southward over Northern Hemisphere continents, causing disruptive long-lasting cold spells. During January 2019, for example, the SPV split into two centers of circulation that drifted southward and brought record-breaking cold to much of eastern North America, Asia, and Eastern Europe (Fig. 15.5).

Research is ongoing to fully understand the dynamics of these sudden stratospheric warming events, which occur approximately once every other winter, particularly to better understand what triggers the initiation of the wave energy propagation from the lower atmosphere into the stratosphere. Some of these events have been associated with a strong ridge that extends northward over the Barents/Kara Seas, connected with low sea ice in this region earlier in the year; thus what began in the early autumn with an unusual loss of sea ice north of western Russia has been suggested to affect winter weather around the Northern Hemisphere for months (e.g., Ref. [54]). Other factors can also cause SPV disruptions, however, and conversely, not all years with low Barents/Kara sea ice will disturb the SPV. While the association is clear, the dynamical mechanisms behind it are not. Research is ongoing to better understand this complex set of interactions [55]; this connection is discussed further in the context of sea ice loss in response to climate change in Section 2.2.

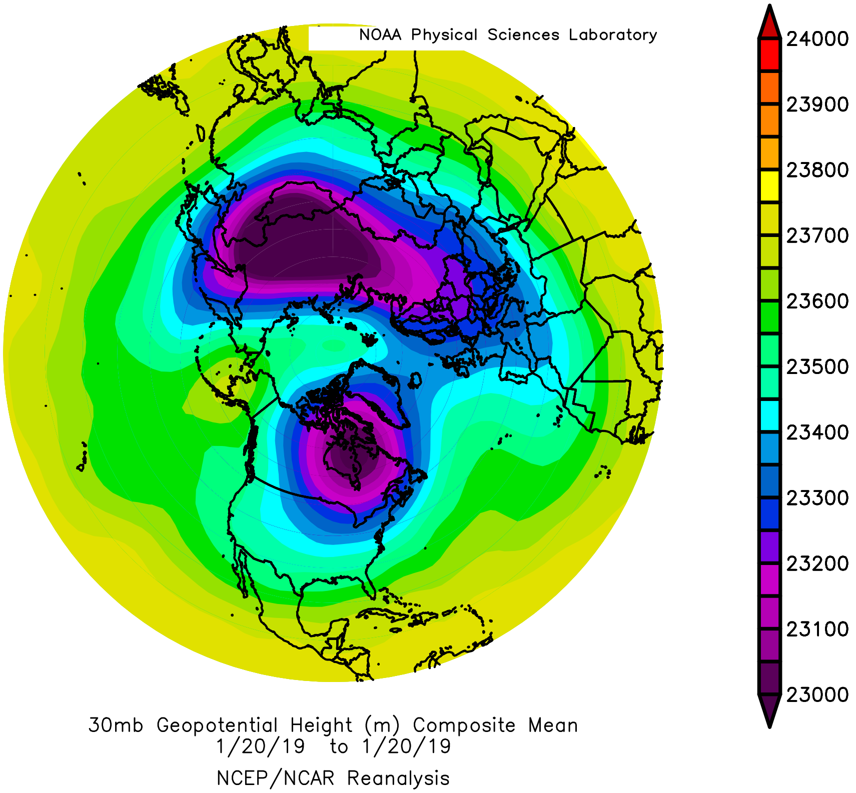

FIGURE 15.5 Geopotential heights (m) at 30 hPa on January 20, 2019, during a major disruption of the stratospheric polar vortex that caused a severe and prolonged cold outbreak in eastern North America. Low heights correspond to cold temperatures. *Data from NOAA/ESRL/PSD.*

1.4.2 Summer

In addition to simply being warmer, background conditions during summertime differ from the cold season in several important ways. First, the stratospheric polar vortex does not exist in summer owing to the absorption of solar energy by the ozone layer and subsequent warming of stratospheric air. Second, the jet streams (subpolar and subtropical) are naturally much weaker during summer because the temperature gradient between low and high latitudes is smaller. Third, the jets shift poleward during the warm season, along with storm tracks and tropical air masses. These changes affect Rossby waves, weather, and connections between the polar regions and midlatitude weather, which will be discussed further in Sections 2.2 and 3.2.

High-amplitude, quasi-stationary, or recurrent Rossby waves have been associated with extreme summer heatwaves [42,11]. Researchers at Potsdam University have proposed that many of the most disruptive recent summer extreme weather events—such as European heatwaves in 2003, 2006, and 2015; the Russian heatwave and Pakistan floods of 2010; drought in the southwestern United States in 2011; and concurrent heatwaves during 2018 in North

America, western Europe, and western Russia—were associated with stagnant weather patterns caused by so-called ***quasi-resonant*** conditions. These conditions are favored when there is a Rossby wave of a specific spatial scale encircling the Northern Hemisphere, along with a waveguide that helps maintain the wave at a particular latitude, trapping the wave energy and amplifying the Rossby waves in the north/south direction. These amplified waves can lead to persistent weather conditions that can cause prolonged heatwaves, drought, and flooding. While the dynamics of this quasi-resonance mechanism are still debated in the scientific community, authors in Refs. [56,57,20] also showed that waveguides are associated with a greater likelihood of high-amplitude quasi-stationary wave activity, with further implications for extreme events [12].

2. Expected changes with climate change

To make confident projections of the future under anthropogenic climate change, we use a combination of climate models, observed trends, and, where possible, fundamental theory. While climate models have many known systematic biases, they are based on the basic laws of physics and remain invaluable tools for establishing causality within the complex climate system. In contrast to phenomena such as temperature increases or rising sea levels, interpreting observed long-term changes in jet dynamics, Rossby waves, and associated extreme weather events is difficult owing to a high level of natural variability in these phenomena. Observed changes will be discussed in more depth in Sections 3.1 and 3.2; here, we describe some of the potential expected changes as predicted by theory and models.

2.1 Jet streams

Many generations of climate models have predicted a general poleward shift of the jets and associated circulation systems in response to anthropogenic climate change. This consensus began to emerge clearly in the Fourth Assessment Report of the IPCC, at least partly as a result of the increased availability of daily model output in the accompanying CMIP3 suite of model simulations [58]. Overall, this response reflects an expansion of the tropical climate zone demarcated by the Hadley cells, a poleward shift of the subtropics and the jets, and a poleward contraction of the midlatitude storm track regions. Although clear in the zonal mean of climate model projections, this simplistic picture obscures considerable regional and seasonal detail in the projected changes [59,60].

Mechanistic understanding of these predicted changes has historically focused on the competing influences of tropical and polar warming; the so-called “tug-of-war” on the jet streams [61]. As the jets owe their existence to the contrast in temperatures between the tropics and the polar regions, perturbations to this temperature contrast are expected to directly impact the jets as well as the associated storm tracks and Hadley cells. A weaker jet could be caused by reduced poleward temperature gradients owing to cooling equatorward of the jet and/or warming on the poleward side.

With anthropogenic climate change, we expect both enhanced warming in the tropical upper troposphere and enhanced warming over the Arctic, known as Arctic amplification. The

tropical warming hot spot results from a reduction in the moist adiabatic lapse rate (the rate at which the temperature of an air parcel containing water vapor decreases with altitude), which is a consequence of increased latent heat release from additional water vapor due to higher temperatures. Evidence for the hot spot exists in observations and climate models [62]. Arctic amplification occurs for multiple reasons, including temperature feedbacks and effects from the loss of sea ice [63]. It remains unclear which will be the dominant mechanism as climate change progresses [64,65], but observations and models agree that Arctic amplification is occurring and will continue into the future. The tropical warming is expected to strengthen the subtropical jets and shift the circulation poleward, while the polar warming is expected, in contrast, to weaken the jets and push them equatorward (e.g., Refs. [66,67]). In other words, whereas Arctic amplification acts to reduce the upper troposphere and lower stratosphere wind speed, tropical upper-tropospheric warming acts to increase it.

Fig. 15.6 shows zonal-mean temperature trends under a 1%/year CO_2 increase model simulation for Northern Hemisphere winter [68]. The tropical upper-tropospheric warming hot spot can be seen as the dark red anomaly over the equator centered at around 200 hPa. Enhanced warming is also seen close to the surface over the Arctic (the dark red anomaly near the surface over the Arctic, on the far right of the figure). These results suggest that Arctic amplification is a relatively shallow phenomenon compared with the full depth of the troposphere, confined to below 700 hPa, approximately the lower 3 km of the atmosphere. This is also the case in reanalyses [69] and in most of the CMIP5 models [70]. Some recent research, however, shows that models with particularly shallow Arctic warming exhibit responses much weaker than observed, while those with deep Arctic warming show responses closer to that observed in the past decades [70].

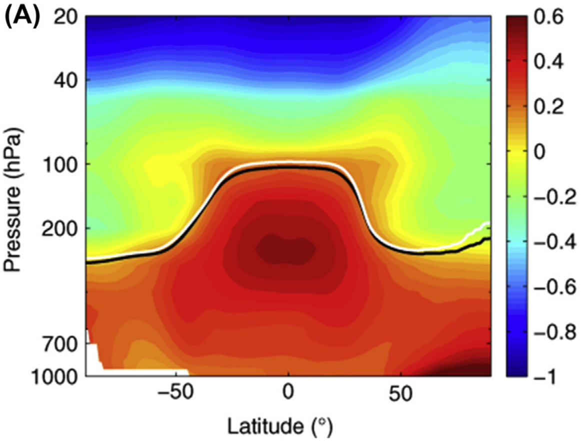

FIGURE 15.6 The simulated ensemble-mean zonal-mean temperature trend (°C/decade) in Northern Hemisphere winter (December, January, and February), as calculated over a period of 70 years in a 1%/year CO_2 increase experiment. The *black and white lines* denote the tropopause height (boundary between troposphere and stratosphere) at the start and end. *From [68].*

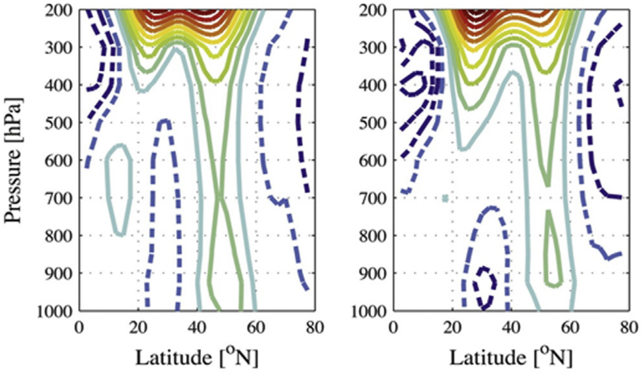

FIGURE 15.7 The simulated ensemble-mean, zonal-mean, zonal wind change in the Northern Hemisphere in winter (November to March) from the end of the 20th century to the end of the 21st century in the CMIP3 project, in the Pacific (left) and Atlantic (right). The contour interval is 0.25 m/s, with positive contour lines solid, negative contour lines dashed, and the zero line removed. *From [71].*

The projected changes in temperature gradients are expected to have a substantial impact on the jet. Fig. 15.7 shows the wintertime zonal-mean zonal wind changes projected by climate model simulations by the end of the 21st century, in response to increased atmospheric CO_2 concentrations. There is an increase in wind speed in the latitude range 20−60°N in both the Pacific and Atlantic sectors at altitudes higher than around the 400−500 hPa pressure surface. The increase is consistent (at least qualitatively) with the thermal wind response to the strengthened meridional temperature gradient in these parts of the atmosphere due largely to the tropical upper-tropospheric warming hot spot. The projection of larger increases higher up in the atmosphere, with weaker increases lower down, means that the models are projecting an increase in ***vertical wind shear***—how much the wind speed changes with height—in the upper troposphere and lower stratosphere region. We show in Section 3.1 evidence of increased vertical wind shear in historic observational data, increasing our confidence in these model projections, and in Section 4.2, we discuss some implications of this for shear-generated clear-air turbulence, with important socioeconomic implications for the aviation sector.

In Fig. 15.7, there is little evidence of a weakening of the jet stream as predicted by Arctic amplification alone, although this analysis focuses on winter. A study looking at more recent climate model projections shows a similar picture for winter, but in summer, there is a projected weakening of the jet in the troposphere [72]. Reanalysis data sets and models typically agree that, in the upper troposphere and lower stratosphere, Arctic amplification loses the tug-of-war to the tropical upper-tropospheric warming hot spot, which acts to increase the equator to pole temperature gradient, but the answer is less clear in the middle troposphere and may be seasonally dependent. Exactly what impact these competing mechanisms throughout the atmospheric column will have on surface weather is the subject of ongoing research and debate.

In addition to this traditional tug-of-war, attention has broadened more recently to other factors that have competing effects on the jets and storm tracks, such as the varied effects of changes in moisture concentrations and cloud properties [73,74]. A plethora of specific theories have been proposed to mechanistically explain the jet response to climate change [75], such that it would seem a daunting challenge for theory alone to solve the issue.

From these considerations, it is clear that the consistent global-average poleward shift predicted by climate models arises from a delicate balance between many competing effects. The predominance of a poleward shift shows that models favor the tropical warming, and the associated dry and moist dynamical processes that affect the temperature and stability in the subtropics as dominant influences on the jets, but the balance is a close one, and models also show a seasonal and regional dependence of projected changes [59]. Overall, the projected model responses in the jets are weaker than the observed natural decadal variability in many cases; this weak response could be an underestimate of the anthropogenic influence on the jets if any of the many competing effects is misrepresented in the models. There is thus currently no strong scientific consensus on whether, under various climate change scenarios, we should expect a weakening, a strengthening, or no change in jet strength [59,76–80]. Some of this discrepancy appears to be from zonal asymmetries in the response, i.e., different responses in the Pacific and Atlantic jets [59], seasonal differences in the response [60], the use of different diagnostics and metrics [81], and/or biases in models and differences in experimental design [82,70].

Driven largely by the dominance of patterns such as the NAO and the Southern Annular Mode in recent observed decadal trends, attention has historically been focused on the jet variability associated with fixed spatial patterns such as these. A key development over the past decade has been the broadening of the discussion to consider the potential changes in Rossby wave activity along the jets under climate change. This was originally driven by concerns that rapid Arctic warming may have been driving apparent changes in wave behavior with associated impacts on extreme weather in the midlatitudes [10,56,78]. These concerns are still being debated (e.g., Ref. [15]), providing a welcome broadening of the focus away from fixed "modes" to considering jet variability more generally. This is discussed further in the following section.

2.2 Rossby waves and associated extreme weather

As discussed earlier, unraveling the impacts of anthropogenic global warming on the jets is a complex task. Understanding the impacts on Rossby waves and extreme weather is, if anything, even more complex. We not only need to understand how jet changes influence atmospheric wave dynamics, but as the jets and waves interact, changes in the waves will lead to changes in the jet and vice versa (e.g., Refs. [83,84]). The potential jet changes introduced earlier may affect wave dynamics, including stationary waves, waveguides, and blocking [85,86,87,88,72].

Even if we did have a clear picture of how changing temperatures affect the jets, the impacts on Rossby waves dynamics and subsequently on extreme events remain unclear, although this is the subject of intense ongoing research [43]. As mentioned in Section 1.2, several studies have found correlations between observed jet strength and measures of "waviness" over the past decades. Combined with modeling studies, these suggest that a weaker jet results in a higher frequency of amplified wave patterns and more blocking events, and vice versa, i.e., a weaker jet is "wavier" [14,76,78,89]. As is often the case with atmospheric dynamics, however, the picture is not completely clear, with some idealized model experiments showing the opposite behavior, with a stronger jet resulting in smaller waves [90]. In addition, one recent study also suggests that while there is a strong relationship between near-surface equator-to-pole temperature gradients and "waviness" of the atmospheric circulation on interannual to decadal timescales, this relationship may not hold for longer-term climate trends [15].

In addition to changes in jet strength, other studies suggest that changes in the latitude of the jet may also play a role in Rossby waves and extreme weather [91]. And, while most studies look at the frequency or strength of events, we might also expect an increase in the size of blocks under climate change conditions [92], with implications for the spatial extent of related heat extremes. This increase was associated with changes in both jet strength and the width of the jet, adding jet width to the list of possible changes that may affect Rossby waves and extreme weather.

Yet another aspect of the climate change response is the ability of the atmospheric jets to act as waveguides, influencing the occurrence of high-amplitude Rossby waves, whether that is through quasi-resonant amplification or the occurrence of quasi-stationary or recurrent Rossby wave events. Because waveguides are created by sharp, strong jets, a weakened jet might be expected to produce fewer, or weaker, waveguides, while a strengthened jet could produce more frequent waveguides. Changes in jet variability, in addition to potential changes in the mean strength, are simulated by models under climate change scenarios [93,59], and these may play an equally important role in waveguide changes. Indeed, Coumou et al. [94] find that jet structure, particularly a split jet, is also key for the formation of waveguides during summer. Using a split jet structure as a proxy for the probability of high-amplitude waves, one study finds that climate models project an increase in the frequency of such conditions in the future, suggesting an increase in the frequency of summer extreme weather events [95].

Additionally, Teng and Branstator [96] suggest that changes in wave sources may be equally important to changes in waveguides, on which there is relatively limited research currently. One study suggests that changes in tropical Rossby wave sources associated with a weakening of tropical circulation in response to anthropogenic warming may explain many stationary wave changes [97]. Projected changes in the zonal winds will also affect the wavenumber of the stationary waves. Current models predict a decrease in the stationary wavenumber in the upper troposphere, which leads to a lengthening of the wavelength of the stationary waves and slower eastward progression. This can have significant consequences for both temperature and precipitation in the extratropics, with predictions of increases in precipitation in some regions and decreases in others [88].

Next, we explore in more detail some of the theory and results that are specific to either the cold or warm season, as in Section 1.4.

2.2.1 *Autumn/winter*

In the cold season, the extent of Arctic sea ice and high-latitude snow cover may play an important role in midlatitude circulation [98,99,100], with obvious implications for a warming climate as sea ice and snow cover decrease. As cautioned earlier in this chapter, however, the mechanisms associated with impacts of Arctic amplification on the midlatitudes, as well as the relative importance compared with other changes forced by anthropogenic warming, is still the subject of intense ongoing research [55,101]. As discussed in Section 1.4, there may also be potential connections between regional sea ice cover and sudden stratospheric warming events, which disrupt the SPV and subsequently impact surface weather.

While overall Arctic warming in the lower atmosphere acts to reduce the zonal-mean north/south temperature gradient and weaken the jet stream's westerly winds, focused warming in localized regions of the Arctic, from sea ice loss for example, may affect the large-scale circulation and temperature patterns in different ways. Regression analysis of observed winter temperature anomalies from 1950 to 2019 shows that temperature anomalies in specific Arctic regions where sea ice retreat has been observed are associated with broader-scale patterns of temperature anomalies extending beyond the Arctic (Fig. 15.8). For example, warm anomalies in the Barents-Kara Seas (Fig. 15.8A) extend over northern Eurasia and are also associated with relatively cool temperatures over midlatitudes of Asia and northern North America. In winters when the whole Arctic is overly warm (Fig. 15.8E), eastern North America and eastern Asia are abnormally cool. These associations between regional Arctic warming and continental temperature anomalies say nothing about causation or mechanisms, however. The patterns may be linked through other factors, such as changes in the tropics and/or natural teleconnections; thus, the research challenge is to unravel how and how much the momentous changes in the Arctic system are influencing the large-scale circulation and under what conditions.

2.2.2 Summer

As discussed in Section 1.4, background conditions during summertime differ from the cold season. Considering Arctic amplification in particular, during summer, the regions of strongest Arctic amplification occur mainly over high-latitude land areas rather than over

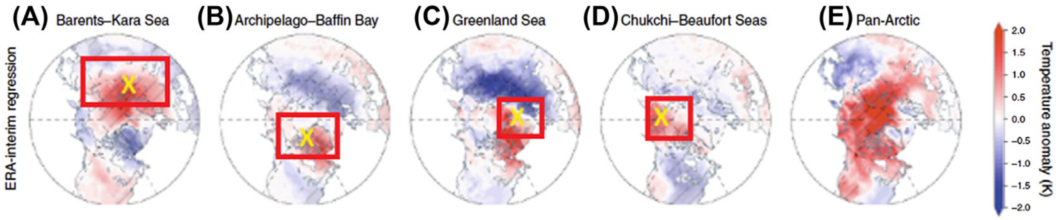

FIGURE 15.8 Observed relationships between winter (DJF) near-surface air temperature anomalies around the Northern Hemisphere on days when regional and pan-Arctic 850 hPa temperature anomalies were between 0.5 and 3.0 standard deviations above the climatological average. Temperature anomalies are for winters during 1950–2019 with temperature anomalies in (A) Barents–Kara Seas, (B) Canadian Archipelago–Baffin Bay, (C) Greenland Sea, (D) Chukchi–Beaufort Seas, and (E) pan-Arctic regressed onto near-surface temperature anomalies. Arctic locations are indicated with a yellow X. Anomalies are calculated relative to climatological averages from 1981 to 2010. *From [55].*

FIGURE 15.9 Schematic of proposed amplification of Rossby waves during summer in response to enhanced warming of high-latitude land areas. Left image illustrates conditions before Arctic warming; right is with Arctic warming, with larger waves in the jet stream. *From [103].*

the Arctic Ocean. These fundamental seasonal differences mean that mechanisms linking the Arctic with midlatitude weather regimes during summer differ markedly from those operating during winter.

In addition to potential changes in jet strength, and subsequently on Rossby wave amplitude, quasi-resonant amplification, introduced in Section 1.4, may play an additional role in summer. During quasi-resonant amplification, an atmospheric waveguide helps amplify Rossby waves under certain conditions. It has been suggested that a split-jet configuration, with one branch flowing along high latitudes and another farther south, is favorable for creating the waveguides that make quasi-resonant amplification more likely [95]. This split-jet seems to be associated with a double peak in the poleward gradient of continental temperature anomalies, providing a mechanism for changing temperatures to change the frequency of quasi-resonant amplification of Rossby waves. This is illustrated by Fig. 15.9, using the example of Arctic amplification as a mechanism for changing the temperature gradients, although as discussed earlier this is not the only mechanism at work. Based on climate model output, one study suggests that the conditions favorable for waveguides are indeed likely to increase in frequency in the future [87], although the impacts of this on extreme events is still a topic of active research [102].

3. Observed changes

3.1 Jet streams

The highly variable nature of jets poses a particular challenge for the identification of emerging signals of anthropogenic climate change. Jets are known to vary naturally on decadal timescales similar to those on which the "fingerprints" of climate change are becoming apparent [104]. Even the magnitude of jet variability has itself been suggested to vary decadally in some cases [105]. As an instructive example, considerable attention focused on the positive trend in the winter NAO, which is reflected in a strengthening and northward shift of the Atlantic jet from the 1960s to the 1990s [106]. However, the supposed trend weakened and then reversed shortly after [107], providing a cautionary example that even apparently strong trends over a period of just a few decades should not automatically be assumed to be a result of climate change.

A more concrete example is that of the recent trend in the Southern Annular Mode (the dominant pattern of natural variability in the circulation of the Southern Hemisphere, largely reflecting north–south shifts of the jet stream) during the southern spring/summer season. This trend is dominated by a poleward shift of the midlatitude jet, which is generally considered to result in large part from the anthropogenic destruction of ozone within the Southern Hemisphere stratospheric polar vortex. Crucially, this conclusion was supported by careful comparisons of the observed trends with those predicted by climate models [108]. This typifies the *detection and attribution* approach that is a cornerstone of IPCC-level climate science. As in other areas of climate science, confidence in any potential emerging signals of change in the jets will not be achieved by observational analysis alone but will require quantitative support from models and, if possible, fundamental theory.

As discussed earlier in this chapter, the Northern Hemisphere subpolar (eddy-driven) jet stream can be influenced by a variety of factors. Because the north/south temperature gradient is the primary driver of jet stream winds, with a strong gradient fueling a strongly sheared jet, anything that affects the strength of the gradient will also influence the jet stream. In recent decades, the Arctic has warmed at a far greater pace than midlatitude regions in general, especially in autumn and winter. This has reduced the north/south gradient in the lower atmosphere and weakened the jet's westerly winds on the poleward side of the jet. This can be seen in Fig. 15.10, which presents recent (2000–19) cold season (November–March) anomalies in air temperature, geopotential height, and zonal (west-to-east) winds from the midlatitudes to the North Pole and from the surface up through the troposphere. Over the past 20 years, air temperatures have risen over the Arctic about three times faster than in midlatitudes, both near the surface and in the upper atmosphere. Because warm air has a lower density than cold air, pressure decreases more slowly with height, causing

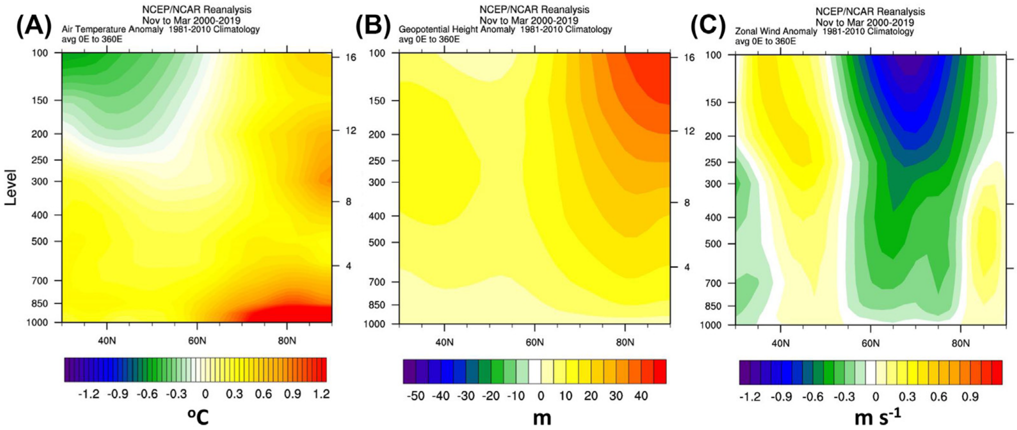

FIGURE 15.10 Latitude/height anomalies in air temperature (A, °C), geopotential height (B, m), and zonal winds (C, m/s) for the cold season (November–March) during 2000–19. Anomalies are calculated relative to 1980–99. *Data were obtained from NOAA/ESRL/PSD.*

a local high pressure and subsequently high ***geopotential height*** (the height above the surface of a given pressure level), increasingly so with altitude (Fig. 15.10B). This reduced pressure over the Arctic weakens the poleward gradient, consistent with the slower zonal-mean zonal winds evident in Fig. 15.10C north of about 55°N, especially in the upper troposphere where the jet stream resides. There is some evidence that weaker jet streams may be more easily diverted from their west-to-east path by various features—such as mountain ranges, areas of convection, and sea surface temperature (SST) anomalies—resulting in a tendency for a wavier jet stream.

As mentioned previously, regional and seasonal variations in temperature changes complicate the story, however. High-latitude warming during recent decades is strongest during fall and winter over the Arctic Ocean (Fig. 15.11A and D) owing primarily to the reduction of sea ice coverage and thickness. As sea ice recedes, additional solar energy is absorbed by the ice-free water rather than being reflected to space by the more reflective ice, causing the ocean to warm. As cold air returns in fall, much of that absorbed heat is returned to the atmosphere, contributing to the changes illustrated in Figs. 15.10 and 15.11. Since 2015, temperature anomalies during winter have exceeded 5°C over much of the central and Pacific sectors of the Arctic Ocean. During spring and summer, however, the location of strongest warming shifts to high-latitude land areas (Fig. 15.11B and C) owing primarily to the substantially earlier melt of spring snow cover on Eurasia and North America [109]. Earlier snow loss allows the underlying soil to dry out and warm sooner, contributing to the positive temperature anomalies observed in spring and summer. These seasonal differences in warming patterns—and their corresponding impacts on regional north/south temperature gradients—will have differing influences on the jet stream, as discussed in Section 2.2. Distinct mechanisms have been proposed linking the various high-latitude warming patterns with large-scale atmospheric responses, but large natural fluctuations in the climate system cause signals of change to be obscured by noise. As the globe continues to warm in response to increasing concentrations of atmospheric greenhouse gas concentrations, signals are expected to strengthen, allowing more robust detection and attribution of changes in the jet stream.

Regional climates can also exhibit pronounced multidecadal patterns of variability. For example, the summer jet stream over the North Atlantic exhibits multidecadal variability in its position as described by the summer NAO [110,111]. This variability is thought to be driven in part by Atlantic multidecadal variability (AMV) in SSTs (e.g., Ref. [112]). This example shows that apparent trends in the jets over short periods should be treated with caution owing to the potential contribution from patterns of natural multidecadal variability.

Study of the North Atlantic region illustrates the tug-of-war between Arctic amplification and the tropical warming hot spot, discussed in Section 2.1. Fig. 15.12 shows the vertical variation of trends in the annual-mean north–south temperature difference across the North Atlantic over the past four decades (since the start of the satellite era). This temperature difference has weakened in the lower atmosphere (below around 450 hPa) due to Arctic amplification, but higher up it has strengthened due to the tropical upper-tropospheric warming hot spot (coupled with lower stratospheric cooling). The weakening at ground level and strengthening in the upper troposphere and lower stratosphere regions are both statistically significant, despite large interannual variability in the position and strength of the North Atlantic subpolar jet stream. However, we note that, although a tropical upper-tropospheric

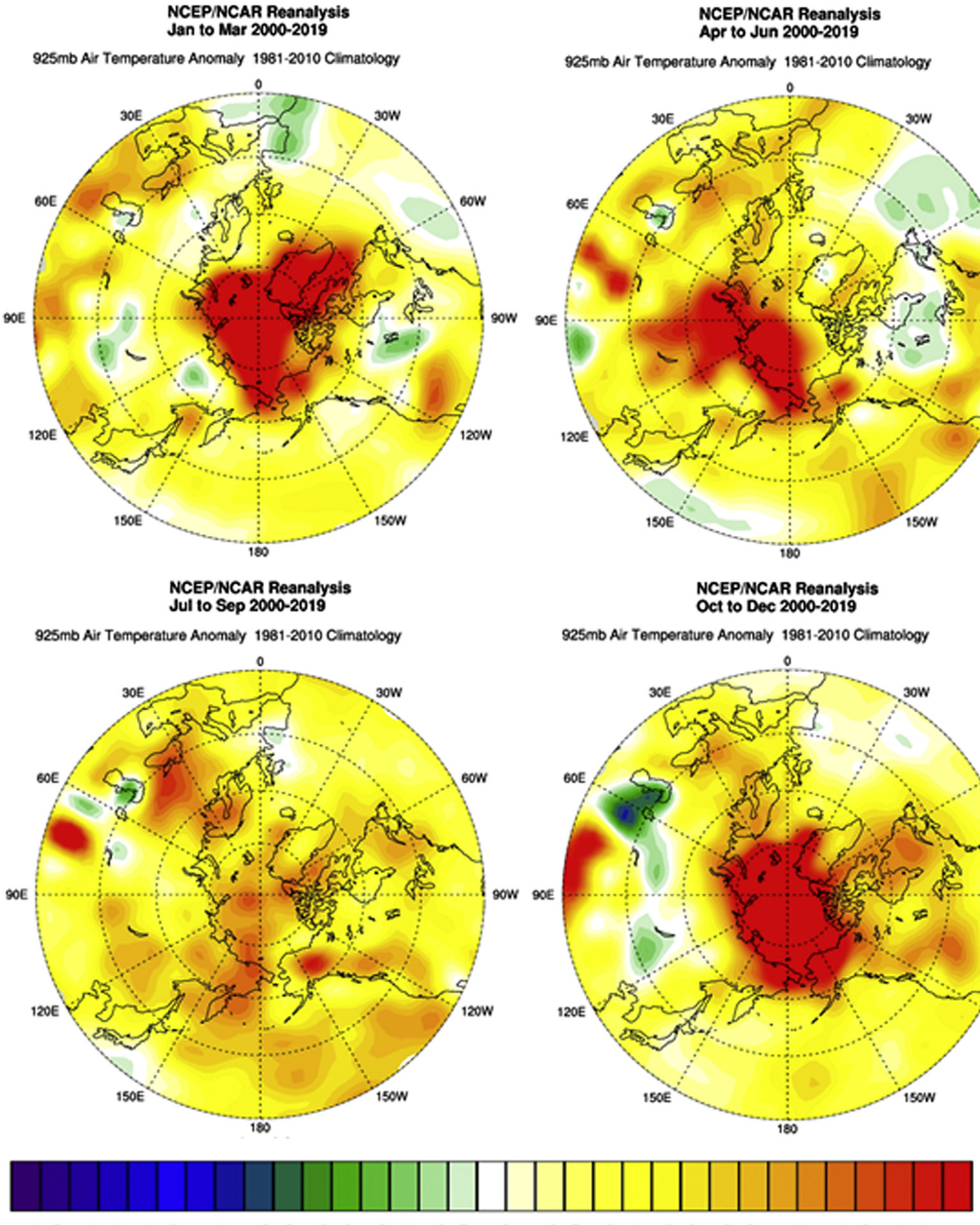

FIGURE 15.11 Anomalies in air temperature (°C) at 925 hPa during 2000–19 (relative to 1980–99) for (A) January–March, (B) April–June, (C) July–September, and (D) October–December. *Data are from NOAA/ESRL/PSD.*

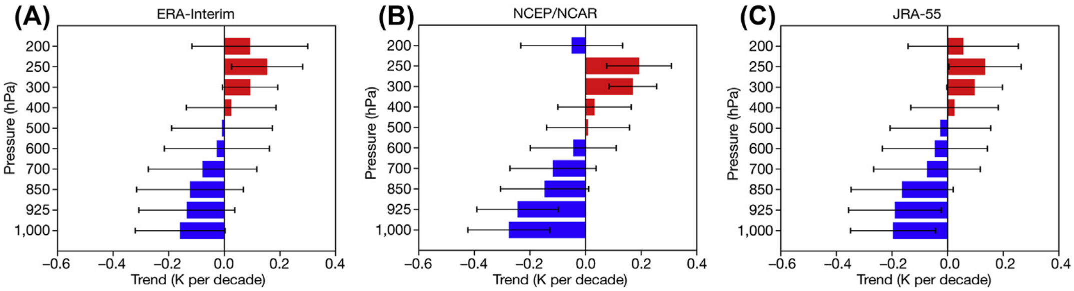

FIGURE 15.12 Vertical profiles of linear trends in annual-mean (all months) north–south temperature difference across the North Atlantic over the period 1979–2017, according to three different reanalysis data sets. The domain being analyzed is 30–70°N and 10–80°W. Error bars represent the 95% confidence intervals. *From [69].*

warming hot spot is expected from basic physical considerations, is present in climate model simulations of the future, and is present in weather balloon observations (albeit taken mainly over land) over the past few decades, evidence for its existence in satellite observations (and hence also reanalysis data) is less clear and still subject to debate.

We saw in Section 2.1 that models and theory predict an increase in vertical wind shear (the change of wind speed with height) in the upper troposphere and lower stratosphere (UTLS). Lee et al. [69] argued that, when attempting to detect long-term trends in the jet streams in the UTLS region, it is better to study changes not in the wind speed, which are subject to the tug-of-war discussed, but rather in the vertical wind shear, which is directly controlled by the local meridional temperature gradients. Effectively, instead of studying the outcome of a delicately balanced tug-of-war, this strategy allows us to study one side of it in isolation, giving a better signal-to-noise ratio and more robust results. What such an analysis reveals is that the annual-mean subpolar jet stream in the North Atlantic sector has become 15% more sheared since satellites began observing it in the late 1970s, as shown in Fig. 15.13. Lee et al. [69] also showed that the stronger shear is quantitatively consistent with the thermal wind response to the changing temperature gradient.

Thus, the vertical shape of the subpolar jet streams is being modified by climate change in a nontrivial manner. Vertical profiles display weaker shear in the lower troposphere, but stronger shear higher up. These changes were first projected by climate model studies but are now clearly evident in historical observational data. The changes are also consistent with our dynamical understanding of the large-scale atmosphere, in terms of thermal wind balance.

3.2 Rossby waves and associated weather extremes

An increase in the frequency of amplified jet stream patterns would result in more persistent weather conditions of various types, which are a primary driver of extreme weather events. Measuring changes in persistence, however, is not straightforward and suffers from the signal-to-noise problem mentioned above for jets. It might seem that air temperature

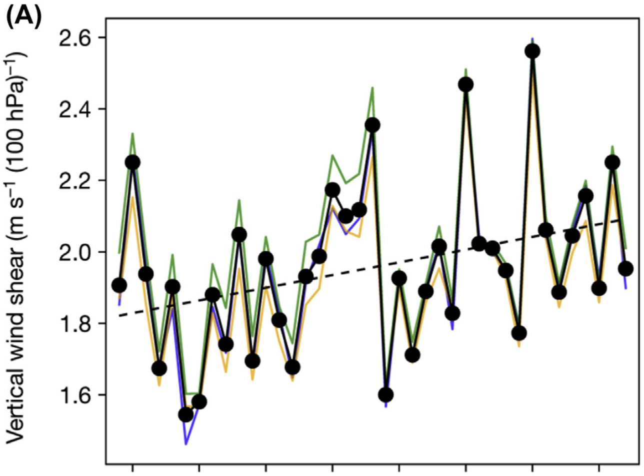

FIGURE 15.13 Time series of annual-mean (all months) vertical shear in zonal wind, spatially averaged in the North Atlantic sector at 250 hPa over the period 1979–2017. Data are presented from three different reanalysis data sets, shown in different colors. Also shown are the mean of the three reanalysis data sets (*solid black line*) and the linear trend in the mean (*dashed black line*). *From [69].*

anomalies at meteorological stations would be good candidates for measuring persistence, but temperatures can be affected by many local factors—such as cloudiness, soil moisture, winds from heterogeneous surfaces (e.g., nearby bodies of water, forest vs. fields, developed vs. undeveloped land), and adiabatic effects owing to nearby elevation—causing temperature variations that are unrelated to the persistence of a weather regime. Precipitation holds greater potential, as synoptic-scale conditions must be right to produce it, but local convection must be taken into account. Another consideration is the shifting background state owing to global warming, which would contribute to a positive trend in the persistence of high-temperature anomalies if the underlying warming trend was not first removed.

While the literature is still relatively sparse on this topic, several recent studies provide evidence for changing persistence of weather regimes around the Northern Hemisphere. Guilbert et al. [113] focused on the northeastern United States and assessed the persistence of daily precipitation events based on 222 weather stations with continuous data extending back at least five decades. They found that the probability of precipitation occurring in two or more consecutive days increased in all months, with strongest positive trends in late spring. Dry spells exhibited positive trends earlier in spring, suggesting that the region is likely to experience larger swings in precipitation regimes. Francis et al. [114] also used precipitation measurements at weather stations as a metric of persistence but extended the domain to the entire lower 48 U.S. from 1950 to 2015. Especially during the latter two decades, they found that the frequency of long-duration wet spells and dry spells (defined as events lasting at least 3 consecutive days) exhibited robust changes regionally and seasonally. The frequency of dry spells increased in most seasons across the southeastern states and high plains, while the frequency of wet spells increased in the eastern part of the country.

Pfleiderer and Coumou [115] investigated the persistence of temperature anomalies, analyzing changes in the length of consecutive anomalously warm or cold days over Northern Hemisphere land areas between 1954 and 2014. They found robust increases in the persistence of both cold and warm anomalies over midlatitude land areas during summer months, particularly the warm events over Europe where heatwaves have been unusually intense in recent years. They also found that persistent summer regimes were more likely to occur when the storm track activity and eddy kinetic energy were weak, which is favored when equator to pole temperature gradients are reduced.

An entirely different approach to measuring changes in weather regime persistence was employed by Francis et al. [114] and Vihma et al. [116], in which a neural network–based pattern identification algorithm was applied to large-scale daily fields of upper-level atmospheric geopotential height anomalies. In both studies, a long-duration event (LDE) was defined as 3 or more consecutive days that the atmosphere resided in the same large-scale pattern. Francis et al. [114] focused on the eastern Pacific/North American sector of the Northern Hemisphere and found that LDEs increased in frequency during 1996–2015 relative to 1976–95 for patterns that feature positive geopotential height anomalies at high latitudes. The authors claim that the recent rapid warming of the Arctic may favor an increased persistence of weather regimes—and therefore extreme events—over North America. The analysis reported in Ref. [116] focused on the Atlantic/Europe region using the same approach and definition of LDEs. Patterns reminiscent of a negative NAO exhibited increasing frequencies of LDEs, while LDEs decreased in patterns similar to a positive NAO. Europe generally experiences anomalously cold (warm) winters during negative (positive) NAO phases; thus despite overall global warming, Europe has continued to experience prolonged cold winter spells.

Disruptive extreme summer weather events around the Northern Hemisphere midlatitudes have increased in frequency and intensity in recent decades, including heatwaves, droughts, and heavy precipitation [117,118]. Some of these extremes are directly related to thermodynamic changes, particularly warming and moistening of the atmosphere, but a growing number of studies suggests that many extremes can only be explained by shifts in atmospheric dynamics, particularly increasing persistence of weather regimes owing to amplified jet stream configurations (e.g., [10,50,56,87,95]).

Recent studies suggest that the quasi-resonant amplification fingerprint has occurred more often in recent decades, especially over Eurasia [95] although the exact causes of these increases are a topic of active research [102]. Some empirical and modeling studies report increased waviness in the summer jet stream in some regions but not consistently around the Northern Hemisphere (e.g. Refs. [76,119,78,120,121]), while other studies find no robust changes in summer waviness (e.g., Refs. [91,122,123]). Discrepancies likely arise through differences in analysis methods, time intervals, and the realism of model simulations.

Various lines of evidence also suggest that westerly winds in the summertime jet stream have weakened, at least partially in response to the observed reduction in the north/south temperature gradient. Linked with a slower summer jet is an observed weakening of storm-track activity and eddy kinetic energy by approximately 15% since the late 1970s, implying that summer weather systems are less potent and more likely to stagnate as frontal systems struggle to make inroads into central continents [77]. While this time period coincides with rapid changes at high latitudes, other factors are also involved, including naturally and anthropogenically fluctuating ocean temperature patterns and large-scale atmospheric variability. Unraveling the causes of extreme summer weather events is an active and fascinating area of research.

4. Future impacts of changing jets

4.1 Persistent weather regimes and extreme weather

As noted in the previous section, an increase in the frequency of amplified jet stream patterns would likely result in more extreme weather events. In addition to an observed increase in the persistence of temperature and precipitation anomalies over the past 60 years, Pfleiderer et al. [124] studied weather persistence in one climate model for a future with 2°C of global warming. They found a 4% increase in the likelihood of anomalously warm summer periods lasting longer than 2 weeks over midlatitude land areas, along with a 26% increase in precipitation events lasting longer than 7 days. Substantial increases (~20%) in the persistence of warm-plus-dry conditions were also projected for eastern North America during summer. These changes were much reduced in projections for 1.5°C global warming, providing further motivation to restrain greenhouse gas emissions as much as possible, thus lessening disruption by extreme weather in the future.

In addition to regional Arctic amplification, the existing state of sub-Arctic/midlatitude ocean temperature patterns can influence the longitudinal axis of ridges and troughs, and consequently, the degree to which a region of Arctic warming can affect the amplitude of the jet stream waves. When a ridge is located in the vicinity of a high-latitude warm anomaly, the additional Arctic heating can intensify the ridge by further elevating geopotential height surfaces, which also tends to amplify the latitudinal breadth of the ridge. When a ridge is strengthened, the downstream trough also tends to deepen. This ridge/trough configuration typically causes couplets of anomalous warm and cold surface conditions that can persist for several days or even weeks if the wave is sufficiently large, as larger waves tend to progress eastward more slowly. In contrast, if existing factors favor a ridge axis position that is not aligned with a region of Arctic warming, little interaction would be expected.

Several recent studies have investigated this potential constructive interference between a naturally varying factor—such as the Pacific Decadal Oscillation (PDO), El Niño Southern Oscillation (ENSO), or the Atlantic Multidecadal Oscillation (AMO)—and factors related to climate change, such as regional Arctic amplification. For example, Sung et al. [125] found that the intensity of ridging off the North American west coast increased under the combined conditions of a positive PDO, which features above-normal SSTs in the eastern North Pacific, along with warm temperatures in the Pacific sector of the Arctic. This amplified ridging typically brings persistent warm, dry weather to western North America along with cold spells and snow storms in the east, a pattern that has predominated since the PDO shifted to a positive phase in late 2013. If the ridge sets up a bit farther west, however, disturbances can ride southward along down its east side and bring heavy precipitation to western states along with bitter cold in the Midwest, which occurred during the winters of 2017/18 and 2018/19. Studies by authors of Refs. [98,126,127,128,129] are consistent with these findings.

A similar constructive relationship has been identified over the Eurasian continent. A climatological ridge tends to exist in the vicinity of the Ural Mountains in western Russia. North of this range lie the Barents and Kara Seas, a region of the Arctic where recent sea ice retreat has been substantial and autumn/winter warming has been pronounced. Because ridging in this area is tied to topography, its location is more consistent than those tied to SST anomalies, and consequently, the impacts on weather patterns have been more regular. Numerous studies have identified a linkage connecting Barents/Kara Seas warming, increased autumn snowfall over Siberia, an amplified ridge/trough jet stream configuration over the continent, and an increased likelihood of persistent cold spells in central and eastern Asia (e.g., [54,100,130–142]). While the direct impact of Barents/Kara Seas warming occurs mainly in late autumn and early winter, a connection with the stratosphere may continue the jet stream's amplified waviness into late winter.

This research all suggests that changes in the jet streams and Rossby waves may play a crucial role in the frequency of persistent and extreme weather under a changing climate. More research is required to better understand the connections and interactions between the many parts of this complex problem to provide more confident projections of future changes in weather extremes.

4.2 More clear-air turbulence for aircraft

We saw in Section 2.1 that climate models project an increase in the vertical wind shear in the upper troposphere and lower stratosphere, and Section 3.1 shows that these projections are supported by observations of current changes. This upper troposphere and lower stratosphere region covers the altitudes at which commercial passenger aircraft typically cruise. Therefore, although we do not live at these altitudes, we do have a special interest in them, because it is where we fly.

The increase in vertical wind shear at aircraft cruising altitudes has unfortunate consequences for air travelers because an invisible form of turbulence is produced in the jet stream whenever the shear is strong. Clear-air turbulence (CAT) is generated in clear skies when the vertical wind shear is stronger than the stratification, as measured by the Richardson number being subcritical ($\mathrm{Ri} < {}^{1}/_{4}$). It follows that climate change is causing an increase in the rate of production of CAT at aircraft cruising altitudes. In particular, when the concentration of CO_2 in the atmosphere is doubled in climate model simulations, the amount of moderate-or-greater CAT within the transatlantic flight corridor in winter increases by 40%–170% [143] and severe CAT increases by 36%–188% [144]. These findings are replicated globally and throughout the year at a range of different flight cruising altitudes, with some midlatitude regions experiencing several hundred percent more CAT by the period 2050–80 in a commonly used future CO_2 scenario [145].

In addition to the impacts on aviation, increased CAT would create more mixing in the upper atmosphere and could therefore also have important (but presently unknown) consequences for atmospheric dynamics and thermodynamics.

5. Summary

Jet streams are powerful currents of air that encircle the globe in both the Northern and Southern Hemispheres in an eastward direction at a height of 10–15 km. Jet streams are important because they create weather systems—areas of both low and high pressure—and steer them along the midlatitudes. They owe their existence to differences in temperature between low and high latitudes as well as the rotation of the Earth. The jet streams normally do not flow in a straight path from west to east, but rather meander in alternating troughs and ridges. These waves are called Rossby waves. Their existence is a direct consequence of the conservation of vorticity.

Rossby waves play an important role in the formation of jet streams via baroclinic instability, which is a consequence of the north–south temperature gradient. Their propagation speed depends on the background winds. Normally the background flow to the east is stronger than the intrinsic propagation speed of the Rossby waves (which is westward in the absence of background winds). However, if these two processes balance, the propagation (transient) waves can become (quasi-) stationary, and even move westward if the background winds are weak and the waves are large. Furthermore, the propagation speed of Rossby waves depends on the wavelength (larger waves travel eastward more slowly) and on latitude. Jets can locally increase the gradient of vorticity, which is the source for Rossby wave growth. From wave theory, it follows that Rossby waves could be inclined toward narrow jet streams and thus can act as a kind of waveguide. It is not clear how changes in the jet stream under climate change conditions may affect these wave guides.

Atmospheric blocking occurs when a jet stream ridge becomes especially large and forms a separate anticyclonic eddy in the flow, which creates a large-scale persistent weather pattern that “blocks” the propagation of Rossby waves. As such blockings can last for 1 or 2 weeks, they can lead to severe weather impacts. The processes that create and destroy blocks, as well as interactions between Rossby waves and blocks, are not yet fully understood, which presents challenges to both weather forecasting and climate projections.

The source of energy for the jet streams is the temperature gradient between subpolar and subtropical regions. As the Arctic at low elevations warms much faster than low latitudes owing to a variety of processes that amplify global warming, the poleward temperature gradient relaxes, and it is hypothesized that the westerly jet stream winds will weaken, causing a “wavier” trajectory and increasing the likelihood of forming blocks and other types of eddies. On the other hand, a hot spot of warming near the level of the tropopause is also expected to occur in response to enhanced release of latent heat as the climate warms. As a consequence, the poleward gradient increases aloft, strengthening the upper-level westerly winds, and altering the vertical stability of the (tropical) atmosphere. Changing poleward temperature gradients at different heights in the atmosphere is also altering the vertical shear in midlatitudes, which may increase clear-air turbulence at altitudes where aircraft fly. It is not yet clear which of the two areas of amplified warming will exert the most influence on the jet streams under climate change conditions, and how they will vary by season, region, and background state of the climate system. These questions are being actively addressed by researchers, as future changes in jet streams will affect weather patterns that have profound impacts on society and ecosystems.

References

[1] T. Woollings, Jet Stream: A Journey Through Our Changing Climate, Oxford University Press, USA, 2019.

[2] Staff members of the Department of Meteorology, University of Chicago, On the general circulation of the atmosphere in middle latitudes, Bull. Am. Meteorol. Soc. 28 (6) (1947) p255−280.

[3] G. Hadley, VI. Concerning the cause of the general trade-winds, Philos. Trans. R. Soc. Lond. 39 (437) (1735) 58−62.

[4] I.M. Held, M. Ting, H. Wang, Northern winter stationary waves: theory and modeling, J. Clim. 15 (16) (2002) 2125−2144.

[5] C. Li, J.J. Wettstein, Thermally driven and eddy-driven jet variability in reanalysis, J. Clim. 25 (5) (2012) 1587−1596.

[6] B.J. Hoskins, I.N. James, Fluid Dynamics of the Mid-latitude Atmosphere, John Wiley & Sons, 2014.

[7] B. Galperin, P.L. Read (Eds.), Zonal Jets: Phenomenology, Genesis, and Physics, Cambridge University Press, 2019.

[8] P.B. Rhines, Waves and turbulence on a beta-plane, J. Fluid Mech. 69 (3) (1975) 417−443.

[9] B.J. Hoskins, D.J. Karoly, The steady linear response of a spherical atmosphere to thermal and orographic forcing, J. Atmos. Sci. 38 (6) (1981) 1179−1196.

[10] V. Petoukhov, S. Rahmstorf, S. Petri, H.J. Schellnhuber, Quasiresonant amplification of planetary waves and recent Northern Hemisphere weather extremes, Proc. Natl. Acad. Sci. U.S.A. 110 (14) (2013a) 5336−5341.

[11] M. Röthlisberger, L. Frossard, L.F. Bosart, D. Keyser, O. Martius, Recurrent synoptic-scale Rossby wave patterns and their effect on the persistence of cold and hot spells, J. Clim. (2019), https://doi.org/10.1175/JCLI-D-18-0664.1.

[12] G. Wolf, D.J. Brayshaw, N.P. Klingaman, A. Czaja, Quasi-stationary waves and their impact on European weather and extreme events, Q. J. R. Meteorol. Soc. 144 (717) (2018) 2431−2448.

[13] D. Barriopedro, R. García-Herrera, A.R. Lupo, E. Hernández, A climatology of northern hemisphere blocking, J. Clim. 19 (6) (2006) 1042−1063.

[14] T. Woollings, E. Barnes, B. Hoskins, Y.-O. Kwon, R.W. Lee, C. Li, E. Madonna, M. McGraw, T. Parker, R. Rodrigues, C. Spensberger, K. Williams, Daily to decadal modulation of jet variability, J. Clim. 31 (2018), https://doi.org/10.1175/JCLI-D-17-0286.1.

[15] R. Blackport, J.A. Screen, Insignificant effect of Arctic amplification on the amplitude of midlatitude atmospheric waves, Sci. Adv. 6 (8) (2020) eaay2880.

[16] B.J. Hoskins, T. Ambrizzi, Rossby wave propagation on a realistic longitudinally varying flow, J. Atmos. Sci. 50 (12) (1993) 1661−1671.

[17] V. Wirth, Waveguidability of idealized midlatitude jets and the limitations of ray tracing theory, Weather Clim. Dynam. Discuss (2020), https://doi.org/10.5194/wcd-2020-3 in review.

[18] G. Branstator, Circumglobal teleconnections, the jet stream waveguide, and the north Atlantic oscillation, J. Clim. 15 (14) (2002) 1893−1910.

[19] G. Branstator, H. Teng, Tropospheric waveguide teleconnections and their seasonality, J. Atmos. Sci. 74 (5) (2017) 1513−1532.

[20] R.H. White, Detecting waveguides for atmospheric planetary waves: connections to extreme weather events, in: J. Brajard, A. Charantonis, C. Chen, J. Runge (Eds.), Proceedings of the 9th International Workshop on Climate Informatics: CI 2019 (No. NCAR/TN-561+PROC), 2019, https://doi.org/10.5065/y82j-f154.

[21] J.M. Wallace, D.S. Gutzler, Teleconnections in the geopotential height field during the Northern Hemisphere winter, Monthly Weather Rev. 109 (4) (1981) 784−812.

[22] D.W. Thompson, S. Lee, M.P. Baldwin, Atmospheric processes governing the northern hemisphere annular mode/North Atlantic oscillation, Geophys. Monogr. Am. Geophys. Union 134 (2003) 81−112.

[23] D.W. Thompson, J.M. Wallace, Annular modes in the extratropical circulation. Part I: month-to-month variability, J. Clim. 13 (5) (2000) 1000−1016.

[24] T. Woollings, A. Hannachi, B. Hoskins, Variability of the North Atlantic eddy-driven jet stream, Q. J. R. Meteorol. Soc. 136 (649) (2010) 856−868.

[25] E. Madonna, C. Li, C.M. Grams, T. Woollings, The link between eddy-driven jet variability and weather regimes in the North Atlantic-European sector, Q. J. R. Meteorol. Soc. 143 (708) (2017) 2960−2972.

[26] S.B. Feldstein, The timescale, power spectra, and climate noise properties of teleconnection patterns, J. Clim. 13 (24) (2000) 4430−4440.

[27] C. Wunsch, The interpretation of short climate records, with comments on the North Atlantic and Southern Oscillations, Bull. Am. Meteorol. Soc. 80 (2) (1999) 245–256.

[28] N. Dunstone, D. Smith, A. Scaife, L. Hermanson, R. Eade, N. Robinson, et al., Skilful predictions of the winter North Atlantic Oscillation one year ahead, Nat. Geosci. 9 (11) (2016) 809–814.

[29] A.A. Scaife, R.E. Comer, N.J. Dunstone, J.R. Knight, D.M. Smith, C. MacLachlan, et al., Tropical rainfall, Rossby waves and regional winter climate predictions, Q. J. R. Meteorol. Soc. 143 (702) (2017) 1–11.

[30] C. Cassou, Intraseasonal interaction between the Madden–Julian oscillation and the north Atlantic oscillation, Nature 455 (7212) (2008) 523–527.

[31] P. Martineau, G. Chen, D.A. Burrows, Wave events: climatology, trends, and relationship to northern hemisphere winter blocking and weather extremes, J. Clim. 30 (15) (2017) 5675–5697.

[32] P. Berrisford, B.J. Hoskins, E. Tyrlis, Blocking and Rossby wave breaking on the dynamical tropopause in the southern hemisphere, J. Atmos. Sci. 64 (8) (2007) 2881–2898.

[33] G. Masato, B.J. Hoskins, T. Woollings, Wave-breaking characteristics of northern hemisphere winter blocking: a two-dimensional approach, J. Clim. 26 (13) (2013) 4535–4549.

[34] C. Weijenborg, H. de Vries, R.J. Haarsma, On the direction of Rossby wave breaking in blocking, Clim. Dyn. 39 (12) (2012) 2823–2831.

[35] N. Nakamura, C.S.Y. Huang, Atmospheric blocking as a traffic jam in the jet stream, Science 361 (6397) (2018) 42–47.

[36] J. Cattiaux, R. Vautard, C. Cassou, P. Yiou, V. Masson-Delmotte, F. Codron, Winter 2010 in Europe: a cold extreme in a warming climate, Geophys. Res. Lett. 37 (20) (2010).

[37] M. Drouard, K. Kornhuber, T. Woollings, Disentangling dynamic contributions to summer 2018 anomalous weather over Europe, Geophys. Res. Lett. 46 (21) (2019) 12537–12546.

[38] R. Seager, M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, et al., Causes of the 2011–14 California drought, J. Clim. 28 (18) (2015) 6997–7024.

[39] J.A. Screen, I. Simmonds, Amplified mid-latitude planetary waves favour particular regional weather extremes, Nat. Clim. Change 4 (8) (2014) 704–709.

[40] H. Teng, G. Branstator, H. Wang, G.A. Meehl, W.M. Washington, Probability of US heat waves affected by a subseasonal planetary wave pattern, Nat. Geosci. 6 (12) (2013) 1056–1061.

[41] N. Harnik, G. Messori, R. Caballero, S.B. Feldstein, The Circumglobal North American wave pattern and its relation to cold events in eastern North America, Geophys. Res. Lett. 43 (20) (2016), 2016GL070760.

[42] G. Fragkoulidis, V. Wirth, P. Bossmann, A.H. Fink, Linking Northern Hemisphere temperature extremes to Rossby wave packets, QJRMS 144 (711) (2018) 553–566.

[43] B. Hoskins, T. Woollings, Persistent extratropical regimes and climate extremes, Curr. Clim. Change Rep. 1 (3) (2015) 115–124.

[44] M. Röthlisberger, S. Pfahl, O. Martius, Regional-scale jet waviness modulates the occurrence of midlatitude weather extremes, Geophys. Res. Lett. 43 (20) (2016), 2016GL070944.

[45] H. Hu, F. Dominguez, Z. Wang, D.A. Lavers, G. Zhang, F.M. Ralph, Linking atmospheric river hydrological impacts on the U.S. West coast to Rossby wave breaking, J. Clim. 30 (9) (2017) 3381–3399.

[46] A.E. Payne, G. Magnusdottir, Dynamics of landfalling atmospheric rivers over the north Pacific in 30 years of MERRA reanalysis, J. Clim. 27 (18) (2014) 7133–7150.

[47] D. Waliser, B. Guan, Extreme winds and precipitation during landfall of atmospheric rivers, Nat. Geosci. 10 (2017) 179.

[48] W.K.M. Lau, K.-M. Kim, The 2010 Pakistan flood and Russian heat wave: teleconnection of hydrometeorological extremes, J. Hydrometeorol. 13 (1) (2011) 392–403.

[49] L. Stadtherr, D. Coumou, V. Petoukhov, S. Petri, S. Rahmstorf, Record Balkan floods of 2014 linked to planetary wave resonance, Sci. Adv. 2 (4) (2016) e1501428.

[50] K. Kornhuber, D. Coumou, E. Vogel, C. Lesk, J.F. Donges, J. Lehmann, R.M. Horton, Amplified Rossby waves enhance risk of concurrent heatwaves in major breadbasket regions, Nat. Clim. Change 10 (1) (2019) 48–53.

[51] L. Brunner, N. Schaller, J. Anstey, J. Sillmann, A.K. Steiner, Dependence of present and future European temperature extremes on the location of atmospheric blocking, Geophys. Res. Lett. 45 (12) (2018) 6311–6320.

[52] S. Pfahl, H. Wernli, Quantifying the relevance of atmospheric blocking for co-located temperature extremes in the Northern Hemisphere on (sub-)daily time scales, Geophys. Res. Lett. 39 (12) (2012), https://doi.org/10.1029/2012GL052261.

[53] A.H. Butler, J.P. Sjoberg, D.J. Seidel, K.H. Rosenlof, A sudden stratospheric warming compendium, Earth Syst. Sci. Data 9 (1) (2017) 63–76.

[54] J. Cohen, J.A. Screen, J.C. Furtado, M. Barlow, D. Whittleston, D. Coumou, J. Francis, K. Dethloff, D. Entekhabi, J. Overland, et al., Recent Arctic amplification and extreme mid-latitude weather, Nat. Geosci. 7 (2014) 627–637.

[55] J. Cohen, X. Zhang, J. Francis, T. Jung, R. Kwok, J. Overland, T. Ballinger, U.S. Bhatt, H.W. Chen, D. Coumou, S. Feldstein, H. Gu, D. Handorf, G. Henderson, M. Ionita, M. Kretschmer, F. Laliberte, S. Lee, H.W. Linderholm, W. Maslowski, Y. Peings, K. Pfeiffer, I. Rigor, T. Semmler, J. Stroeve, P.C. Taylor, S. Vavrus, T. Vihma, S. Wang, M. Wendisch, Y. Wu, J. Yoon, Divergent consensuses on Arctic amplification influence on mid-latitude severe winter weather, Nat. Clim. Change 10 (2020) 20–29.

[56] V. Petoukhov, S. Rahmstorf, S. Petri, H.J. Schellnhuber, Reply to screen and simmonds: from means to mechanisms [review of reply to screen and simmonds: from means to mechanisms], Proc. Natl. Acad. Sci. U.S.A. 110 (26) (2013b) E2328.

[57] J.A. Screen, I. Simmonds, Exploring links between Arctic amplification and mid-latitude weather, Geophys. Res. Lett. 40 (2013) 959–964, https://doi.org/10.1002/grl.50174.

[58] J.H. Yin, A consistent poleward shift of the storm tracks in simulations of 21st century climate, Geophys. Res. Lett. 32 (18) (2005).

[59] E.A. Barnes, L. Polvani, Response of the midlatitude jets, and of their variability, to increased greenhouse gases in the CMIP5 models, J. Clim. 26 (18) (2013) 7117–7135.

[60] I.R. Simpson, T.A. Shaw, R. Seager, A diagnosis of the seasonally and longitudinally varying midlatitude circulation response to global warming, J. Atmos. Sci. 71 (7) (2014) 2489–2515.

[61] I.M. Held, Large-scale dynamics and global warming, Bull. Am. Meteorol. Soc. 74 (2) (1993) 228–242.

[62] S. Sherwood, N. Nishant, Atmospheric changes through 2012 as shown by iteratively homogenized radiosonde temperature and wind data (IUKv2), Environ. Res. Lett. 10 (2015) 054007, https://doi.org/10.1088/1748-9326/10/5/054007.

[63] M.C. Serreze, R.G. Barry, Processes and impacts of Arctic amplification: a research synthesis, Global Planet. Change 77 (1) (2011) 85–96.

[64] A. Dai, D. Luo, M. Song, J. Liu, Arctic amplification is caused by sea-ice loss under increasing CO_2, Nat. Commun. 10 (1) (2019) 121.

[65] F. Pithan, T. Mauritsen, Arctic amplification dominated by temperature feedbacks in contemporary climate models, Nat. Geosci. 7 (3) (2014) 181–184.

[66] H.S. Baker, T. Woollings, C. Mbengue, Eddy-driven jet sensitivity to diabatic heating in an idealized GCM, J. Clim. 30 (16) (2017) 6413–6431.

[67] A.H. Butler, D.W. Thompson, R. Heikes, The steady-state atmospheric circulation response to climate change–like thermal forcings in a simple general circulation model, J. Clim. 23 (13) (2010) 3474–3496.

[68] G.K. Vallis, P. Zurita-Gotor, C. Cairns, J. Kidston, Response of the large-scale structure of the atmosphere to global warming, Q. J. R. Meteorol. Soc. 141 (2015) 1479–1501, https://doi.org/10.1002/qj.2456.

[69] S.H. Lee, P.D. Williams, T.H.A. Frame, Increased shear in the North Atlantic upper-level jet stream over the past four decades, Nature 572 (2019) 639–642, https://doi.org/10.1038/s41586-019-1465-z.

[70] S. He, X. Xu, T. Furevik, Y. Gao, Eurasian cooling linked to the vertical distribution of Arctic warming, Geophys. Res. Lett. (2020), https://doi.org/10.1029/2020GL087212.

[71] S.C. Delcambre, D.J. Lorenz, D.J. Vimont, J.E. Martin, Diagnosing northern hemisphere jet portrayal in 17 CMIP3 global climate models: twenty-first-century projections, J. Clim. 26 (2013) 4930–4946, https://doi.org/10.1175/JCLI-D-12-00359.1.

[72] R.C.J. Wills, R.H. White, X.J. Levine, Northern hemisphere stationary waves in a changing climate, Curr. Clim. Change Rep. 5 (4) (2019) 372–389.

[73] P. Ceppi, D.L. Hartmann, Connections between clouds, radiation, and midlatitude dynamics: a review, Curr. Clim. Change Rep. 1 (2) (2015) 94–102.

[74] T.A. Shaw, M. Baldwin, E.A. Barnes, R. Caballero, C.I. Garfinkel, Y.T. Hwang, et al., Storm track processes and the opposing influences of climate change, Nat. Geosci. 9 (9) (2016) 656–664.

[75] T.A. Shaw, Mechanisms of future predicted changes in the zonal mean mid-latitude circulation, Curr. Clim. Change Rep. 5 (4) (2019) 345–357.

[76] J. Cattiaux, Y. Peings, D. Saint-Martin, N. Trou-Kechout, S.J. Vavrus, Sinuosity of midlatitude atmospheric flow in a warming world, Geophys. Res. Lett. 43 (2016) 8259–8268, https://doi.org/10.1002/2016GL070309.

[77] D. Coumou, J. Lehmann, J. Beckmann, The weakening summer circulation in the Northern Hemisphere mid-latitudes, Science 348 (2015) 324–327.

[78] J.A. Francis, S.J. Vavrus, Evidence linking Arctic amplification to extreme weather in mid-latitudes, Geophys. Res. Lett. 39 (2012) L06801, https://doi.org/10.1029/2012GL051000.

[79] W. Iqbal, W.-N. Leung, A. Hannachi, Analysis of the variability of the North Atlantic eddy-driven jet stream in CMIP5, Clim. Dyn. (2017), https://doi.org/10.1007/s00382-017-3917-1.

[80] Y. Peings, J. Cattiaux, S.J. Vavrus, G. Magnusdottir, Projected squeezing of the wintertime North-Atlantic jet, Environ. Res. Lett. 13 (7) (2018) 074016. ERL [Web Site].

[81] T. Woollings, M. Blackburn, The North Atlantic jet stream under climate change and its relation to the NAO and EA patterns, J. Clim. 25 (3) (2011) 886–902.

[82] J.A. Francis, Why are Arctic linkages to extreme weather still up in the air? BAMS 98 (12) (2017) 2551–2557.

[83] J. Kidston, G.K. Vallis, S.M. Dean, J.A. Renwick, Can the increase in the eddy length scale under global warming cause the poleward shift of the jet streams? J. Clim. 24 (14) (2011) 3764–3780.

[84] D.J. Lorenz, Understanding midlatitude jet variability and change using Rossby wave chromatography: wave–mean flow interaction, J. Atmos. Sci. 71 (10) (2014) 3684–3705.

[85] E.A. Barnes, D.L. Hartmann, Detection of Rossby wave breaking and its response to shifts of the midlatitude jet with climate change, J. Geophys. Res. 117 (D9) (2012), https://doi.org/10.1029/2012JD017469.

[86] C. Huntingford, D. Mitchell, K. Kornhuber, D. Coumou, S. Osprey, M. Allen, Assessing changes in risk of amplified planetary waves in a warming world, Atmos. Sci. Lett. 20 (8) (2019) 741.

[87] M.E. Mann, S. Rahmstorf, K. Kornhuber, B.A. Steinman, S.K. Miller, S. Petri, D. Coumou, Projected changes in persistent extreme summer weather events: the role of quasi-resonant amplification, Sci. Adv. 4 (2018) eaat3272.

[88] I.R. Simpson, R. Seager, M. Ting, T.A. Shaw, Causes of change in Northern Hemisphere winter meridional winds and regional hydroclimate, Nat. Clim. Change 6 (1) (2016) 65–70.

[89] Y. Peings, J. Cattiaux, S. Vavrus, G. Magnusdottir, Late twenty-first-century changes in the midlatitude atmospheric circulation in the CESM large ensemble, J. Clim. 30 (15) (2017) 5943–5960.

[90] P. Hassanzadeh, Z. Kuang, B.F. Farrell, Responses of midlatitude blocks and wave amplitude to changes in the meridional temperature gradient in an idealized dry GCM, Geophys. Res. Lett. 41 (14) (2014) 5223–5232.

[91] E.A. Barnes, Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes, Geophys. Res. Lett. 40 (17) (2013) 4734–4739.

[92] E. Nabizadeh, P. Hassanzadeh, D. Yang, E.A. Barnes, Size of the atmospheric blocking events: scaling law and response to climate change, Geophys. Res. Lett. 46 (22) (2019) 13488–13499.

[93] E.A. Barnes, D.L. Hartmann, Influence of eddy-driven jet latitude on North Atlantic jet persistence and blocking frequency in CMIP3 integrations, Geophys. Res. Lett. 37 (23) (2010), https://doi.org/10.1029/2010GL045700.

[94] D. Coumou, V. Petoukhov, S. Rahmstorf, S. Petri, H.J. Schellnhuber, Quasi-resonant circulation regimes and hemispheric synchronization of extreme weather in boreal summer, Proc. Natl. Acad. Sci. U.S.A. 111 (34) (2014) 12331–12336.

[95] M.E. Mann, S. Rahmstorf, K. Kornhuber, B.A. Steinman, S.K. Miller, D. Coumou, Influence of anthropogenic climate change on planetary wave resonance and extreme weather events, Sci. Rep. 7 (2017) 45242.

[96] H. Teng, G. Branstator, Amplification of waveguide teleconnections in the boreal summer, Curr. Clim. Change Rep. 5 (4) (2019) 421–432.

[97] R.J. Haarsma, F. Selten, Anthropogenic changes in the Walker circulation and their impact on the extra-tropical planetary wave structure in the Northern Hemisphere, Clim. Dyn. 39 (7) (2012) 1781–1799.

[98] I. Cvijanovic, B.D. Santer, C. Bonfils, D.D. Lucas, J.C.H. Chiang, S. Zimmerman, Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall, Nat. Commun. 18 (2017), https://doi.org/10.1038/s41467-017-01907-4.

[99] J.A. Screen, C. Deser, D.M. Smith, X. Zhang, R. Blackport, P.J. Kushner, T. Oudar, K.E. McCusker, L. Sun, Consistency and discrepancy in the atmospheric response to Arctic sea-ice loss across climate models, Nat. Geosci. 11 (3) (2018) 155–163.

[100] P. Zhang, Y. Wu, I.R. Simpson, K.L. Smith, X. Zhang, B. De, P. Callaghan, A stratospheric pathway linking a colder Siberia to Barents-Kara Sea sea ice loss, Sci. Adv. 4 (2018) 7, https://doi.org/10.1126/sciadv.aat6025.

[101] J.E. Overland, K. Dethloff, J.A. Francis, R.J. Hall, E. Hanna, S.-J. Kim, J.A. Screen, T.G. Shepherd, T. Vihma, Nonlinear response of mid-latitude weather to the changing Arctic, Nat. Clim. Change 6 (11) (2016) 992–999.
[102] R.M. Horton, J.S. Mankin, C. Lesk, E. Coffel, C. Raymond, A review of recent advances in research on extreme heat events, Curr. Clim. Change Rep. 2 (2016) 242–259.
[103] D. Coumou, G. Di Capua, S. Vavrus, et al., The influence of Arctic amplification on mid-latitude summer circulation, Nat. Commun. 9 (2018) 2959. https://doi.org/10.1038/s41467-018-05256-8.
[104] I.R. Simpson, C. Deser, K.A. McKinnon, E.A. Barnes, Modeled and observed multidecadal variability in the North Atlantic jet stream and its connection to sea surface temperatures, J. Clim. 31 (20) (2018) 8313–8338.
[105] T. Woollings, D. Barriopedro, J. Methven, S.W. Son, O. Martius, B. Harvey, et al., Blocking and its response to climate change, Curr. Clim. Change Rep. 4 (3) (2018) 287–300.
[106] J.W. Hurrell, Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation, Science 269 (5224) (1995) 676–679.
[107] J. Cohen, M. Barlow, The NAO, the AO, and global warming: how closely related? J. Clim. 18 (21) (2005) 4498–4513.
[108] N.P. Gillett, D.W. Thompson, Simulation of recent Southern Hemisphere climate change, Science 302 (5643) (2003) 273–275.
[109] K.E. Kunkel, D.A. Robinson, S. Champion, X. Yin, T. Estilow, R.M. Frankson, Trends and extremes in northern hemisphere snow characteristics, Curr. Clim. Change Rep. 2 (2016) 65–73, https://doi.org/10.1007/s40641-016-0036-8.
[110] C.K. Folland, J. Knight, H.W. Linderholm, D. Fereday, S. Ineson, J.W. Hurrell, The summer North Atlantic oscillation: past, present, and future, J. Clim. 22 (2009) 1082–1103, https://doi.org/10.1175/2008JCLI2459.1.
[111] R. Sutton, B. Dong, Atlantic Ocean influence on a shift in European climate in the 1990s, Nat. Geosci. 5 (2012) 788–792, https://doi.org/10.1038/ngeo1595.
[112] C.H. O'Reilly, T. Woollings, L. Zanna, The dynamical influence of the Atlantic multidecadal oscillation on continental climate, J. Clim. 30 (2017) 7213–7230, https://doi.org/10.1175/JCLI-D-16-0345.1.
[113] J. Guilbert, A.K. Betts, D.M. Rizzo, B. Beckage, A. Bomblies, Characterization of increased persistence and intensity of precipitation in the northeastern United States, Geophys. Res. Lett. 42 (2015) 1888–1893, https://doi.org/10.1002/2015GL063124.
[114] J.A. Francis, N. Skific, S.J. Vavrus, North American weather regimes are becoming more persistent: is Arctic amplification a factor? Geophys. Res. Lett. 45 (2018) https://doi.org/10.1029/2018GL080252.
[115] P. Pfleiderer, D. Coumou, Quantification of temperature persistence over the Northern Hemisphere land-area, Clim. Dyn. (2017), https://doi.org/10.1007/s00382-017-3945-x.
[116] T. Vihma, R. Graversen, L. Chen, D. Handorf, N. Skific, J.A. Francis, N. Tyrrell, R. Hall, E. Hanna, P. Uotila, K. Dethloff, A.Y. Karpechko, H. Björnsson, J.E. Overland, Effects of the tropospheric large-scale circulation on European winter temperatures during the period of amplified Arctic warming, Int. J. Clim. (2019), https://doi.org/10.1002/joc.6225.
[117] Insurance Information Institute, 2019. https://www.iii.org/fact-statistic/facts-statistics-global-catastrophes.
[118] S. Rahmstorf, D. Coumou, Increase of extreme events in a warming world, Proc. Natl. Acad. Sci. U.S.A. 108 (2011) 17905–17909.
[119] G. Di Capua, D. Coumou, Changes in meandering of the northern hemisphere circulation, Environ. Res. Lett. 11 (2016), https://doi.org/10.1088/1748-9326/11/9/094028.
[120] J.A. Francis, S.J. Vavrus, Evidence for a wavier jet stream in response to rapid Arctic warming, Environ. Res. Lett. 10 (2015), https://doi.org/10.1088/1748-9326/10/1/014005.
[121] S.J. Vavrus, F. Wang, J.E. Martin, J.A. Francis, Y. Peings, J. Cattiaux, Changes in North American atmospheric circulation and extreme weather: influence of Arctic amplification and northern hemisphere snow cover, J. Clim. 30 (2017), https://doi.org/10.1175/JCLI-D-16-0762.1.
[122] J.A. Screen, I. Simmonds, Caution needed when linking weather extremes to amplified planetary waves [Review of Caution needed when linking weather extremes to amplified planetary waves], Proc. Natl. Acad. Sci. U.S.A. 110 (26) (2013) E2327.
[123] E.A. Barnes, J.A. Screen, The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? WIREs Clim. Change (2015) https://doi.org/10.1002/wcc.337.
[124] P. Pfleiderer, C.-F. Schleussner, K. Kornhuber, D. Coumou, Summer weather becomes more persistent in a 2°C world, Nat. Clim. Change (2019), https://doi.org/10.1038/s41558-019-0555-0.

[125] M.-K. Sung, B.-M. Kim, E.-H. Baek, Y.-K. Lim, S.-J. Kim, Arctic-North Pacific coupled impacts on the late autumn cold in North America, Environ. Res. Lett. 11 (2016) 084016, https://doi.org/10.1088/1748-9326/11/8/084016.

[126] P.A. Knapp, P.T. Soulé, Spatio-temporal linkages between declining Arctic sea-ice extent and increasing wildfire activity in the western United States, Forests 8 (9) (2017) 313, https://doi.org/10.3390/f8090313.

[127] J.-S. Kug, J.-H. Jeong, Y.-S. Jang, B.-M. Kim, C.K. Folland, S.-K. Min, S.-W. Son, Two distinct influences of Arctic warming on cold winters over North America and East Asia, Nat. Geosci. 8 (2015) 759–762, https://doi.org/10.1038/ngeo2517.

[128] M.-Y. Lee, C.-C. Hong, H.-H. Hsu, Compounding effects of warm sea surface temperature and reduced sea ice on the extreme circulation over the extratropical North Pacific and North America during the 2013–2014 boreal winter, Geophys. Res. Lett. 42 (2015) 1612–1618, https://doi.org/10.1002/2014GL062956.

[129] Y. Tachibana, K.K. Komatsu, V.A. Alexeev, L. Cai, Y. Ando, Warm hole in Pacific Arctic sea ice cover forced mid-latitude Northern Hemisphere cooling during winter 2017–18, Nat. Sci. Rep. 9 (2019) 5567, https://doi.org/10.1038/s41598-019-41682-4.

[130] B.-M. Kim, S.-W. Son, S.-K. Min, J.-H. Jeong, S.-J. Kim, X. Zhang, T. Shim, J.-H. Yoon, Weakening of the stratospheric polar vortex by Arctic sea-ice loss, Nat. Commun. 5 (2014) 4646.

[131] M. Honda, J. Inoue, S. Yamane, Influence of low Arctic sea-ice minima on anomalously cold Eurasian winters, Geophys. Res. Lett. 36 (2009) L08707, https://doi.org/10.1029/2008GL037079.

[132] R. Jaiser, K. Dethloff, D. Handorf, A. Rinke, J. Cohen, Impact of sea ice cover changes on the Northern Hemisphere atmospheric winter circulation, Tellus A: Dyn. Meteorol. Oceanogr. 64 (1) (2012), https://doi.org/10.3402/tellusa.v64i0.11595.

[133] R. Jaiser, K. Dethloff, D. Handorf, Stratospheric response to Arctic sea ice retreat and associated planetary wave propagation changes, Tellus A: Dyn. Meteorol. Oceanogr. 65 (1) (2013), https://doi.org/10.3402/tellusa.v65i0.19375.

[134] J.C. Furtado, J.L. Cohen, A.H. Butler, et al., Eurasian snow cover variability and links to winter climate in the CMIP5 models, Clim. Dyn. 45 (2015) 2591–2605. https://doi.org/10.1007/s00382-015-2494-4.

[135] Y. Wu, K.L. Smith, Response of northern hemisphere midlatitude circulation to arctic amplification in a simple atmospheric general circulation model, J. Clim. 29 (2016) 2041–2058. https://doi.org/10.1175/JCLI-D-15-0602.1.

[136] J. Zhang, W. Tian, M.P. Chipperfield, F. Xie, J. Huang, Persistent shift of the Arctic polar vortex towards the Eurasian continent in recent decades, Nat. Clim. Change (2016), https://doi.org/10.1038/nclimate3136.

[137] M. Kretschmer, D. Coumou, J.F. Donges, J. Runge, Using causal effect networks to analyze different Arctic drivers of midlatitude winter circulation, J. Clim. 29 (2016), https://doi.org/10.1175/JCLI-D-15-0654.1.

[138] T. Nakamura, K. Yamazaki, K. Iwamoto, M. Honda, Y. Miyoshi, Y. Ogawa, Y. Tomikawa, J. Ukita, The stratospheric pathway for Arctic impacts on midlatitude climate, Geophys. Res. Lett. 43 (2016), https://doi.org/10.1002/2016GL068330.

[139] Y. Zou, Y. Wang, Y. Zhang, J.-H. Koo, Arctic sea ice, eurasia snow, and extreme winter haze in China, Sci. Adv. (2017), https://doi.org/10.1126/sciadv.1602751.

[140] K.E. McCusker, P.J. Kushner, J.C. Fyfe, M. Sigmond, V.V. Kharin, C.M. Bitz, Remarkable separability of circulation response to Arctic sea ice loss and greenhouse gas forcing, Geophys. Res. Lett. 44 (2017) 7955–7964, https://doi.org/10.1002/2017GL074327.

[141] K. Ye, T. Jung, T. Semmler, The influences of the Arctic troposphere on the midlatitude climate variability and the recent Eurasian cooling, J. Geophys. Res.: Atm. 123 (2018), https://doi.org/10.1029/2018JD028980.

[142] K. Hoshi, J. Ukita, M. Honda, T. Nakamura, K. Yamazaki, Y. Miyoshi, R. Jaiser, Weak stratospheric polar vortex events modulated by the Arctic sea-ice loss, J. Geophys. Res.: Atm. 124 (2019) 858–869. https://doi.org/10.1029/2018JD029222.

[143] P.D. Williams, M. Joshi, Intensification of winter transatlantic aviation turbulence in response to climate change, Nat. Clim. Change 3 (2013) 644–648, https://doi.org/10.1038/nclimate1866.

[144] P.D. Williams, Increased light, moderate, and severe clear-air turbulence in response to climate change, Adv. Atmos. Sci. 34 (2017) 576–586, https://doi.org/10.1007/s00376-017-6268-2.

[145] L.N. Storer, P.D. Williams, M.M. Joshi, Global response of clear-air turbulence to climate change, Geophys. Res. Lett. 44 (2017) 9976–9984, https://doi.org/10.1002/2017GL074618.