From Atmospheric Waves to Heatwaves
A Waveguide Perspective for Understanding and Predicting Concurrent, Persistent, and Extreme Extratropical Weather
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ABSTRACT: A notable number of high-impact weather extremes have occurred in recent years, often associated with persistent, strongly meandering atmospheric circulation patterns known as Rossby waves. Because of the high societal and ecosystem impacts, it is of great interest to be able to accurately project how such extreme events will change with climate change, and to predict these events on seasonal-to-subseasonal (S2S) time scales. There are multiple physical links connecting upper-atmosphere circulation patterns to surface weather extremes, and it is asking a lot of our dynamical models to accurately simulate all of these. Subsequently, our confidence in future projections and S2S forecasts of extreme events connected to Rossby waves remains relatively low. We also lack full fundamental theories for the growth and propagation of Rossby waves on the spatial and temporal scales relevant to extreme events, particularly under strongly nonlinear conditions. By focusing on one of the first links in the chain from upper-atmospheric conditions to surface extremes—the Rossby waveguide—it may be possible to circumvent some model biases in later links. To further our understanding of the nature of waveguides, links to persistent surface weather events and their representation in models, we recommend exploring these links in model hierarchies of increasing complexity, developing fundamental theory, exploiting novel large ensemble datasets, harnessing deep learning, and increased community collaboration. This would help increase understanding and confidence in both S2S predictions of extremes and of projections of the impact of climate change on extreme weather events.

KEYWORDS: Dynamics; Rossby waves; Extreme events
Extreme weather events can have a devastating impact on human lives across the globe. According to a 2020 report by the United Nations Office for Disaster Risk Reduction (UNDRR), extreme weather events have “come to dominate the disaster landscape in the 21st century” (UNDRR 2020). The disastrous European heatwave of 2003 killed between 30,000 and 70,000 people (Robine et al. 2008; García-Herrera et al. 2010). More recent examples include the Californian drought and eastern U.S. severe cold during winter 2013/14 (Wang et al. 2014; Hartmann 2015), heatwaves in Europe in 2010 (Barriopedro et al. 2011), 2018 (Liu et al. 2020), and 2019 (Mitchell et al. 2019; Christidis et al. 2020), the unprecedented western North America heatwave and subsequent wildfires in late June 2021 (Philip et al. 2021), as well as heatwaves and flooding events across Europe (Kreienkamp et al. 2021), and flooding in China and India, during July 2021. Some recent research has suggested that persistent and extreme weather events may be increasing in frequency (e.g., Francis et al. 2018), with potential connections to anthropogenic climate change (Mann et al. 2017; Pfleiderer et al. 2019; Kornhuber and Tamarin–Brodsky 2021); however, there is ongoing debate about the specific mechanisms at play in such connections, in particular the role of changing atmospheric dynamics (e.g., Barnes and Screen 2015; Francis 2017; Huguenin et al. 2020; Stendel et al. 2021).

One of the most pressing questions for climate scientists to answer is “How will the amplitude and frequency of extreme events change with anthropogenic warming?” The answer can be considered to have two parts: thermodynamic and dynamic, with substantial differences in our confidence of future projections for each of these. Indeed, “nearly everything we have any confidence in when it comes to climate change is related to global patterns of surface temperature, which are primarily controlled by thermodynamics” (Shepherd 2014). This thermodynamic portion deals with the direct consequences of a warming atmosphere and ocean on extreme events: warmer average surface temperatures mean more heatwaves and fewer cold snaps; warmer air usually contains more moisture, leading to heavier extreme rainfall (e.g., Fischer and Knutti 2016); warmer ocean temperatures lead to sea level rise, which contributes to increased coastal flooding. Within this thermodynamic response there is still a great deal to be uncovered, particularly on smaller time and spatial scales, but much of the underlying physics is well understood on larger scales. Conversely, the response of atmospheric dynamics to anthropogenic warming, and how this will affect extreme events, is much less clear (Shepherd 2014). Potential changes to large-scale atmospheric circulation, which is critical to many (although certainly not all) extreme events, is the subject of intense ongoing research and debate (e.g., Blackport et al. 2019; Teng and Branstator 2019; Cohen et al. 2020). At the heart of the debate are future changes in the location and strength of the extratropical atmospheric jets—narrow bands of strong winds flowing largely west to east—and in the waviness of these jet streams.

In addition to the uncertainty in climate change projections of extreme events, there is also a considerable skill gap in our ability to predict the probability of extreme event occurrence.
on a subseasonal-to-seasonal (S2S) time scale (e.g., Prodhomme et al. 2022), i.e., beyond the limit of numerical weather predictions (~2 weeks). Current S2S forecast models are able to provide skillful forecasts of some extreme temperature events, for example the 2003 European heatwave (e.g., Weisheimer et al. 2011), although others, such as the Russian heatwave of 2010, are less well predicted (Dole et al. 2011; Katsafados et al. 2014). There is evidence that the same waviness of the jet stream that is important for climate projections of extreme events may play a role in enhancing S2S predictability (Grazzini and Vitart 2015).

Waves on the atmospheric jets, known as Rossby waves (Rossby 1939; Platzman 1968), contribute to many extreme weather events (e.g., Bosart et al. 1996, 2017; Screen and Simmonds 2014; Chen et al. 2015; Hoskins and Woollings 2015; Wirth et al. 2018), including temperature extremes (Marengo et al. 2002; Teng et al. 2013; Parker et al. 2014; McKinnon et al. 2016; Wolf et al. 2018; Röthlisberger et al. 2019), as well as extreme precipitation and/or flooding (Blackburn et al. 2008; Schubert et al. 2011; Hirata and Grimm 2016; de Vries 2021). Rossby waves manifest as meridional undulations in the extratropical atmospheric circulation, resulting from the conservation of a dynamical property known as potential vorticity (PV); PV is a function of both relative and planetary vorticity, and of static stability. Owing to the rotation and the sphericity of Earth, planetary vorticity increases toward the poles; thus, a parcel of air moving poleward (under fixed static stability) must, in order to conserve PV, reduce its relative vorticity by rotating in an anticyclonic sense—the subsequent pattern of atmospheric motion leads to Rossby waves, consisting of consecutive regions of anomalous cyclonic and anticyclonic vorticity. Rossby waves occur continuously in the atmosphere, forced by upper-level divergence of air from diabatic heating, growth of baroclinic instabilities, or interactions of flow with orography (Hoskins and Karoly 1981; Held et al. 2002; White et al. 2021). The large-scale seasonal mean circulation patterns are shaped by Rossby waves, often referred to as “stationary waves” in reference to their persistence over entire seasons (e.g., Held et al. 2002; Wills et al. 2019). In contrast, typical Rossby waves of interest for persistent weather extremes, particularly heatwaves or cold snaps, persist for several days to several weeks, and have wavelengths of ~3,000–6,000 km, generally smaller than the stationary waves.

A grounding theory of the linear behavior of Rossby waves and their propagation was well developed in the second half of the twentieth century; however, there has recently been a renaissance of interest in the scientific community in Rossby waves, largely focused on their connections to extreme weather events (e.g., Palmer 2013; Hoskins and Woollings 2015; Wirth et al. 2018). Extreme weather events can arise from Rossby waves with either anomalously high stationarity/persistence (e.g., Schubert et al. 2011; Trenberth and Fasullo 2012; Teng et al. 2013; Chen et al. 2015; Wolf et al. 2018; Röthlisberger et al. 2019), and/or anomalously high amplitude (e.g., Blackburn et al. 2008; Petoukhov et al. 2013; Screen and Simmonds 2014; McKinnon et al. 2016; Röthlisberger et al. 2016; Rodrigues and Woollings 2017). Anomalous persistence of usually transient Rossby waves results in waves described as “quasi stationary.” These quasi-stationary waves remain in approximately the same location with approximately the same phase for several days to weeks; this can lead to extreme events such as multiple days of rainfall leading to flooding, or extended heatwaves. Longer duration extreme weather events can be particularly damaging (e.g., Gasparrini and Armstrong 2011; Stadtherr et al. 2016) and may be amplified due to land–atmosphere feedbacks (Miralles et al. 2019). Understanding the mechanisms behind these persistent synoptic-scale Rossby waves is therefore critically important.

Figure 1 showcases three months during the Northern Hemisphere summer in which persistent high-amplitude Rossby waves occurred associated with persistent extreme weather events, with data from ERA5 (Hersbach et al. 2020). The Rossby waves are visible in the monthly mean meridional winds $\nu$ (colored shading); the bottom panel shows the 1979–2020 June–July (JJ) climatology for comparison. Comparison with the climatology shows that the midlatitude Rossby wave seen between 30° and 60°N in each of these extreme months is, broadly speaking, a strong
amplification of the climatological pattern; however, the strong Rossby wave at higher latitudes present in each of these extreme months is barely noticeable in the climatology.

During summer, the anticyclonic anomalies of Rossby waves are often associated with hot surface temperature anomalies; this is largely due to a combination of adiabatic warming and the anomalous radiative heating associated with clear-sky conditions (Pfahl and Wernli 2012; Bieli et al. 2015). During the months illustrated in Fig. 1, numerous long-duration (weekly–monthly) temperature extremes occurred, the approximate locations of which are shown by red (hot) and blue (cold) diamonds (temperature extremes based on National Centers for Environmental Information 2013, 2018; Im et al. 2019; Lu et al. 2020; Wilcke et al. 2020). The association of these persistent temperature extremes with the Rossby wave vorticity anomalies can be seen—hot anomalies occur in the anticyclonic regions (southerly winds to the west, northerly winds to the east).

Practically, the study of Rossby wave impacts can be split into two subproblems: 1) the forcing of waves and 2) wave propagation and amplification away from the source region. This latter category has overall received relatively less attention within recent decades; we suggest that a revival of this field of study could play a key role in helping solve our projection and prediction problems. In both the future projection and S2S prediction of extremes, we are asking a lot from climate models to accurately simulate extreme events associated with persistent or
high-amplitude Rossby waves: accurately simulating potentially highly nonlinear upper-level Rossby wave dynamics, including wave sources, propagation pathways, and the stationarity or amplitude growth of waves; reproducing observed connections between the upper and lower regions of the troposphere and through the boundary layer; and simulating land–atmosphere interactions including feedbacks from soil moisture. An exciting research direction that may help reduce the negative impacts of model biases across these multiple links, with the potential to move the field forward significantly, is to address this problem through a causal chain of physical processes linking extreme weather events to Rossby waves via Rossby waveguides.

**Atmospheric Rossby waveguides**

Rossby waveguides act in a manner analogous to other physical waveguides, constraining the Rossby wave perturbations of the atmospheric flow. A fundamental theory of the linear propagation of Rossby waves away from a source region was developed in the 1980s and 1990s (Hoskins and Karoly 1981; Branstator 1983; Held 1983; Hoskins and Ambrizzi 1993). This work introduces the concept of a *refractive index* for the atmosphere, with waves refracted toward regions of higher refractive index. This framing allows for “ray tracing” of Rossby waves, to determine their expected propagation pathways for a given background flow. The general circulation of the atmosphere is such that the refractive index generally increases toward the equator and thus waves are typically refracted toward the tropics (e.g., Hoskins and Karoly 1981). Atmospheric jets, however, can produce a local maximum (in the meridional direction) in the refractive index. Theoretical arguments lead to the conclusion that, if conditions are right, i.e., jets are particularly strong and narrow, *turning latitudes* exist on both sides of the jet for waves of particular wavenumbers (Hoskins and Karoly 1981; Hoskins and Ambrizzi 1993). Between these two turning latitudes a waveguide exists according to that theory, and much of the synoptic-scale wave energy would be confined to propagate zonally within the jet–waveguide region. This theory was originally developed to describe the behavior of stationary waves in climatological flow (Hoskins and Karoly 1981; Hoskins and Ambrizzi 1993); however, subsequent work has shown that the theory may also help explain observed subseasonal waves (Branstator 2002; Manola et al. 2013; Branstator and Teng 2017), including model biases (Li et al. 2020).

The theory of waveguide behavior discussed above depends on the Wentzel–Kramers–Brillouin (WKB) theorem; here, this translates to an assumption that the background flow varies gradually relative to the scale of the waves (Hoskins and Ambrizzi 1993). The validity of this assumption is even described in the original papers as “dubious” (Hoskins and Karoly 1981) and “questionable” (Hoskins and Ambrizzi 1993); however, the resulting theory has been useful in describing a number of observations and model results (e.g., Hoskins and Karoly 1981; Hoskins and Ambrizzi 1993; Branstator 2002; Manola et al. 2013; White et al. 2017; Li et al. 2020). An alternative perspective of Rossby waveguides considers strong gradients of potential vorticity as waveguides (e.g., Platzman 1968; Swanson et al. 1997; Martius et al. 2010; Wirth 2020). In a highly idealized framework this theory considers Rossby waves as waves propagating along a step function separating a region of high PV from a region of lower PV. Due to the relationship between PV and horizontal gradients of wind, these areas of strong PV gradients correspond to jets; they can thus also be considered jet waveguides. Hereafter we use “Rossby waveguide” to refer to waveguides formed by a strong narrow jet, without necessarily distinguishing between these two theoretical frameworks.

Qualitative metrics of the presence of Rossby waveguides are shown in the solid (strong jet) and dotted (high horizontal isentropic gradient of PV) black contours in Fig. 1. In the following paragraph we discuss these two different proxies, but first we note the obvious collocation between the Rossby waves and the Rossby waveguides. The presence of a double waveguide
structure over Eurasia (one in midlatitudes and one in higher latitudes) is clear in all the extreme months and absent in the climatology; this is consistent with work suggesting the importance of a double jet structure for some extratropical extreme weather events (Kornhuber et al. 2017; Xu et al. 2021), although others have suggested that the waves themselves may contribute to the double jet features (Wirth and Polster 2021).

For waveguides based on the presence of a strong jet, shown in the solid contours in Fig. 1, we do not focus on the exact linear theory (i.e., presence of turning latitudes); instead, we look more generally for strong jets, as described by Manola et al. (2013). Indeed, it remains unclear to what degree the established linear theory holds for high-amplitude events on synoptic temporal and spatial scales. The solid black contours in Fig. 1 show the 12.5, 17.5, and 22.5 m s\(^{-1}\) contours of the time mean zonal wind. Conversely, to illustrate the approximate location of waveguides based on the PV gradient waveguide theory, the dotted contours in Fig. 1 show regions of high horizontal gradients of ln(PV) on isentropic surfaces intersecting the tropopause (see Martius et al. 2010). We plot a single relatively high-value contour (0.001 km\(^{-1}\)) to illustrate regions of high isentropic horizontal gradients, i.e., regions likely to show strong waveguiding behavior; these are plotted for two isentropic surfaces, 320 and 340 K, to show the waveguides at two separate latitudes. The values are smoothed in longitude using a Savitzky–Golay filter (window size: 101; polynomial order: 3) to simplify the plots. The congruence between the two waveguide frameworks (refractive index via jets, and horizontal PV gradients) can be seen in the strong overlap between the two waveguide proxies shown in the top two panels of Fig. 1.

On climatological time scales the causal relationship between waveguides and meridionally constrained Rossby waves has been well established (e.g., Hoskins and Karoly 1981; Hoskins and Ambrizzi 1993; Branstator 2002); in Fig. 1, a correlation on this shorter, monthly, time scale is suggested but of course this alone does not imply causality. Previous research has suggested causal connections on subseasonal time scales (Branstator 2002; Manola et al. 2013; Branstator and Teng 2017); however, more research is required to better ascertain the relationship between waves and waveguides on the time scales relevant to subseasonal persistent weather extremes. Also apparent in Fig. 1, particularly in the solid black zonal wind contours, is that the jet waveguides are impacted and shaped by the waves themselves—the waves are not a small perturbation to the background flow. This, in conjunction with known feedbacks from waves to the background flow (e.g., Edmon et al. 1980), makes the separation of waves and background flow difficult, particularly for high-amplitude events typically associated with extreme weather (e.g., Wirth and Polster 2021).

Based on theoretical arguments, a causal connection from waveguides to high-amplitude or quasi-stationary Rossby waves on these temporal and spatial scales certainly seems plausible. In the absence of a waveguide, Rossby waves tend to propagate toward the tropics, where they break and their energy dissipates (e.g., Hoskins and Karoly 1981; Abatzoglou and Magnusdottir 2004). Waveguides help constrain Rossby wave energy in the extratropics, thus creating the potential for waves with stronger vorticity (circulation) anomalies, i.e., higher-amplitude waves, and thus more impact on surface weather. Persistent waveguides may also produce a consistent propagation pathway for waves, which may result in persistent/quasi-stationary Rossby waves. The jet waveguide perspective may therefore be useful in understanding both the amplitude and the persistence of anomalous Rossby waves. Rossby waveguides have been invoked to help explain particular types of large-scale patterns of variability and teleconnections (Simmons et al. 1983; Wallace et al. 1988; Hsu and Lin 1992; Ambrizzi et al. 1995; Swanson et al. 1997; Branstator 2002; Branstator and Teng 2017), including persistent patterns that can lead to extratropical weather extremes (e.g., Petoukhov et al. 2013; White et al. 2019). Variability of the waveguides on subseasonal time scales (e.g., Branstator 2002; Branstator and Teng 2017), also apparent in Fig. 1 (contrast the extreme months with the climatology),

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provides the potential that such waveguides might be useful in making progress on the projection and prediction problems.

**Toward solving the projection and prediction problems**

We have the most confidence in projections of future climates when observed changes, modeled projections, and basic theory all give similar answers; this is the case, for example, for large-scale patterns of surface temperature change (IPCC 2021). For extreme and/or persistent events, however, we are limited in multiple ways: we do not have a long enough observation period for these relatively rare events; models have biases in simulating extremes (e.g., Angélil et al. 2016); and, in contrast to thermodynamical changes, we do not have strong widely accepted underlying theories for many potential changes in circulation that are likely critical for understanding changes in extreme events.

The authors believe that increased understanding of the role of jet waveguides in extreme weather events could give us a powerful tool with which to analyze and understand the occurrence of such events, and to make significant progress on solving the projection and prediction problems. If the background atmosphere that contains the waveguides has a longer time scale than the wave itself, then that could give us enhanced predictability. If climate models can more accurately simulate waveguides and their projected changes than the behavior of the waves themselves, this could give us more robust/accurate climate projections. The schematic in Fig. 2 shows our interpretation of the connections between waveguides and the projection and prediction problems of extreme events, and how fundamental theory and dynamical model analysis can work in tandem to make progress on these problems. Analysis of waveguides in complex GCMs, rooted in both established and new understanding of the underlying theory, may provide a pathway forward.

Several important scientific questions in this field remain; here we summarize the research themes we think are critical for helping explore/realize the potential of waveguides to improve projections and S2S predictions of persistent extreme weather events.

*The separation of “waves” and “background flow.”* The definition of a *background flow* in the context of understanding waves and their impacts is a “quite formidable problem” (Pedlosky 1987; Held et al. 2002). Frequently, perhaps because of its simplicity, the zonal mean circulation has been used as the background flow on which waves (deviations from the zonal mean) are traveling (e.g., Hoskins and Karoly 1981; Petoukhov et al. 2013); however, there are potential issues with this, in particular once the flow becomes substantially nonlinear (Wirth and Polster 2021). Such a separation into a zonal mean and disturbance quantities is “primarily a mathematical device and may not be the most natural physical separation in all cases” (Andrews et al. 1987). Indeed, for extreme events that involve wave propagation in only part of the hemisphere, considering a zonally symmetric background state may miss important interactions. Alternatives include a time mean background.

![Fig. 2. Schematic of the connections between waveguides (white box) and the projection and predictability problems (orange box), via fundamental theory (green rectangles), process understanding (blue diamond), and dynamical model analysis (purple circles).](image-url)
state (e.g., Held et al. 2002), the most frequent flow configuration (Swanson 2001), longitudinal filtering (e.g., Starr 1950; White 2019), or a “azonalized” background state (Nakamura and Zhu 2010; Methven and Berrisford 2015). Recent work has also attempted to move away from seasonal time means (White 2019; Rudeva and Simmonds 2021), but the separation of waves and background flow in these cases remains ambiguous. That there is still an increasing number of methods of separating waves and the background flow serves to confirm that this is indeed a formidable problem, and further research efforts are required.

**Definition of waves.** Connected to the issues of separating and defining a background flow comes issues of defining and diagnosing waves themselves, particularly when nonlinear effects are significant. Vorticity anomalies in the atmosphere exist on a spectrum from individual blocks (Rex 1950; Nakamura and Huang 2018), through localized Rossby wave packets (Zimin et al. 2003; Huang and Nakamura 2016), to circumglobal Rossby waves (Branstator 2002). Waves are described as circumglobal when they extend (almost) around an entire latitude band (Branstator 2002; Branstator and Teng 2017); this circumglobal behavior has been connected to extreme events (Harnik et al. 2016; Wang et al. 2013) and has particular relevance for concurrent extremes occurring across a hemisphere (Kornhuber et al. 2020). Despite these different terms being used throughout the scientific literature, there is no clear physical definition of the differences between them or of the relative importance of different underlying mechanisms in each circumstance.

**Definition of a Rossby waveguide.** Even if we had an unambiguous background flow it remains unclear what the “best” jet waveguide definition is, and to what degree the “refractive index” and “PV gradient” approaches provide similar results (Hoskins and Ambrizzi 1993; Martius et al. 2010; Wirth 2020). Both approaches are currently used; however, there is little understanding of the degree to which the refractive index theory remains useful when applied specifically to high-amplitude waves, as is typical for extreme events (Wirth and Polster 2021). Another potential issue with the refractive index concept is its binary approach: either a waveguide for a certain wavenumber exists, or it does not. The PV approach is better able to capture the more realistic concept of a continuous distribution of possible PV gradients, with stronger gradients preventing greater loss of wave energy into the tropics (Wirth 2020).

**Connecting waves, jets, waveguides, and extreme weather.** It is well established that high-amplitude quasi-stationary Rossby waves can lead to extreme events (e.g., Terao 1999; Schubert et al. 2011; Hoskins and Woollings 2015; Wolf et al. 2018), but how and why waves become quasi stationary, high amplitude, or both is less clear. Determining which mechanisms dominate, and understanding the fundamental physics of these mechanisms, including the role of nonlinear dynamics, are key next steps. Current avenues include “recurrent” Rossby waves (Röthlisberger et al. 2019); quasi resonance, a theory suggesting that waveguide-trapped free Rossby waves resonate with stationary forcing from orography or diabatic heating (Petoukhov et al. 2013); various potential connections between waveguides or PV gradients and blocking (Nakamura and Huang 2018; Luo et al. 2019); and the observed preference for particular phases, or “phase locking,” of Rossby waves (e.g., Ding and Wang 2005; Sato and Takahashi 2006; Kosaka et al. 2009; Screen and Simmonds 2014; Kornhuber et al. 2020). One theory of the connection between jets and waves, with particular relevance for understanding future changes, is the idea that Arctic amplification will lead to a weaker jet, which will lead to stronger waves (Francis and Vavrus 2012), although this idea has not been widely accepted (e.g., Barnes and Screen 2015; Huguenin et al. 2020; Stendel et al. 2021). Interestingly, the waveguide perspective would suggest an alternative scenario: weaker jets would most likely lead to weaker waveguides (Manola et al. 2013), and
thus potentially to smaller midlatitude wave amplitudes. Tierney et al. (2021) suggest that consideration of moist processes may be key to understanding these contradictions. Determining how these conflicting arguments can be resolved may be critical in understanding how persistent Rossby waves, and related extreme events, may change in frequency or amplitude with a warming climate.

Moving forward

The field of atmospheric Rossby waves is still full of scientific challenges (Hoskins and Woollings 2015; Cohen et al. 2020). The stakes are high with the potential for increased understanding of how extreme weather events may change under anthropogenic climate change, as well as improving the S2S prediction of such events. We suggest that Rossby waveguides may be easier to predict and project than the waves themselves. As summarized in the schematic in Fig. 2, we believe the field can take significant steps forward by better understanding the fundamental role of extratropical Rossby waveguides in these phenomena.

Avenues of research with particularly fertile ground for progress include the following:

- Combining research on fundamental theory (Vallis 2016; Emanuel 2020) with studies using the full hierarchy of models, in particular idealized models (Vallis et al. 2018), to better understand interactions between waveguides, waves, and extremes, and to better understand the mechanisms behind waves that become quasi stationary/persistent.
- Study of the range of validity, and limitations, of current theories of Rossby waves and waveguides to understand at what time and spatial scales causal connections exist; this includes establishing whether a causal relationship exists from waveguides to waves on the time scales relevant for extreme weather events and S2S forecasting, and if so, how this impacts S2S predictability and prediction skill.
- Studying the representation of, and biases in, waveguides, waves, and connections to the surface in dynamical models, including large ensembles of fully coupled dynamical Earth system climate projection and S2S models; this includes the role of internal variability and forced trends, understanding mechanisms behind model biases, and understanding the impacts of those biases on simulations of present and future climate.
- Harnessing novel computational analysis methods such as machine/deep learning to detect and, crucially, to understand and explain, relationships and predictors (e.g., McGovern et al. 2019).

Research that is more open and collaborative, e.g., by openly sharing generated/processed datasets and analysis/diagnostics code online (e.g., Kluyver et al. 2016; McKiernan et al. 2016), will be hugely beneficial. Similarly, we recommend collaboration within the community to establish clear definitions and terms, and consistent usage, for key concepts (e.g., block vs Rossby wave packet vs Rossby wave train). With the unabating increase in global research output in the present interconnected age (Geerts 1999), access to scientific papers, ideas, datasets, and models feels almost inexhaustible; time is now a key limiting factor for scientists. With care, the expansion of online connectivity established during the global COVID-19 pandemic could be harnessed to strengthen exchange between theoreticians, data analysts, and synopticians from across the globe, and make better use of scientist’s expertise and time. Indeed, part of the legacy of Carl Gustaf Rossby, for whom Rossby waves are named, includes his success at fostering interactions and collaborations between scientists from many different countries and institutions during the first half of the twentieth century (Phillips 1998; Bolin 1999).

To further foster collaborative environments, we invite the community to acknowledge that the level of consensus we would like to have may not be achievable in the near future, and comprehensive theories may remain elusive. Disagreements between different methods, particularly where different assumptions are made, can be utilized to learn more about the
underlying physics, including the applicability of assumptions on specific temporal and/or spatial scales. We also encourage all authors to provide more open and honest discussion of the limitations and caveats of their research within the papers themselves to invite further discussion, debate, collaboration, and, ultimately, progress.

Working together to increase our understanding of the role of jet waveguides in the relevant processes and mechanisms that lead to high-amplitude and/or persistent Rossby waves brings the promise of societally relevant scientific discoveries. This research field has the potential to greatly increase our understanding of the occurrence of persistent extreme events, improve our prediction of them on subseasonal-to-seasonal time scales, and reduce uncertainty in the expected changes in the frequency or magnitude of extreme events in our future, providing the potential to mitigate at least some of the worst impacts of anthropogenic climate change.

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