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REPLY

Reply to Comment on 'Extreme weather events in early summer 2018 connected by a recurrent hemispheric wave-7 pattern'

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Abstract

Circumglobal teleconnections from wave-like patterns in the mid-latitude jets can lead to synchronized weather extremes in the mid-latitudes of Northern and Southern hemispheres. The simultaneous occurrence of record breaking and persistent northern hemisphere temperature anomalies in Summer 2018 were previously discussed in the context of a persistent zonally elongated wave-7 pattern that stretched over large parts of the northern hemisphere over an extended time and let to considerable societal impacts. Various diagnostics have been put forward to quantify and detect such wave patterns, many of which incorporate low-pass time filtering to separate signal from noise. In this response we argue that advancing our understanding of the large-scale circulation's response to anthropogenic climate change and reducing associated uncertainties in future climate risk requires a diverse range of perspectives and diagnostics from both the climate and weather research communities.

1. On the importance of selecting process relevant time scales in climate research

Time averaging is a common practice in climate science. Serving as a filter for noise and short-term variability, applying time averages helps to distinguish between short term fluctuations of day to day weather and long term persistent patterns associated with slowly moving components of the earth system associated with climate variability or change.

Modern reanalysis data sets, such as ERA5 offer climate data at an unprecedented hourly resolution at 36 vertical levels with an approximate horizontal resolution of 31 km at the Earth's-surface. A reasonable approach in data formatting is to trim time and spatial scales to the type of climate or weather phenomena one aims at investigating. To study long-term global climate change annual means on a global scale might be most informative [1]. To investigate certain modes of variability, such as the El Niño–Southern Oscillation (ENSO) [2] or the Madden–Julian oscillation [3] one would choose monthly to seasonal averages. For the study of individual storms or heavy precipitation events daily or sub-daily data would be most useful [4]. When studying the large-scale atmospheric patterns that serve as steering patterns and background conditions for higher-frequency weather phenomena, weekly to monthly averages are typically most insightful. The same applies to the study of persistent heatwaves, which emerge and decline on weekly [5–7] to monthly timescales [8].

2. On the existence of circumglobal teleconnections in the midlatitude jets

Globally concurrent and locally record-breaking temperatures driven by thermodynamic and dynamical responses to anthropogenic activity have revived the interest in the investigation of recurrent large-scale atmospheric patterns [9–15]. Circumglobal teleconnections (CGTs) formed and guided by the mid-latitude jet streams can be mathematically described by Rossby wave theory and have led to established theories behind CGTs over nearly a century of research [16].

A rich body of literature on recurrent stationary patterns in the midlatitude circulation exists going back decades. This body of literature describes CGTs from a phenomenological and theoretical standpoint and provides evidence for their existence using observational data and models of various complexity [17–19]. Branstator [20] showed the existence of CGTs in the Northern Hemisphere's winter (December–February), which when a disturbance is placed in the jet core, would be guided by mid-latitude waveguides in a quasi-circumglobal manner. Ding and Wang [21] showed the existence of such patterns in the Northern Hemisphere summer highlighting strong links to the Indian summer monsoon and ENSO. Assessing the leading modes of the Northern Hemisphere summer circulation, Schubert *et al* [22, 23] showed that large-scale circumglobal patterns also exist on submonthly timescales. A common feature of these studies is the employment of sub-monthly to seasonal timescales to identify, characterize and suggest theoretical models to explain the emergence of CGT, their paths and locations. In his comment to our paper Kornhuber *et al* [24] (K19 hereafter), Jacopo Riboldi (JR hereafter) states that K19 would have claimed to identify 'a novel type of CGT mediated by Rossby waves.' Given the numerous papers from various different groups and different generations of atmospheric scientists (also cited and discussed in K19), the above cited claim of JR cannot be considered true.

3. Quasistationary Rossby waves and synchronized weather extremes

Furthermore, quasi-stationary Rossby waves acting on timescales from weeks to months can form CGTs with strong impacts on local weather and extremes. Teng *et al* [25] identified a submonthly wave-5 CGT with strong links to U.S. heatwaves. Petoukhov *et al* [10, 26] showed that several high impact heatwaves in spring to summer were associated with high amplitude hemispheric slow-moving Rossby waves assessed on monthly and sub-monthly timescales. In addition, several singular high impact extremes were discussed in the context of quasi-stationary waves, including the 2003 European heatwave [7, 9, 15], the concurrent 2010 Russian heatwave and Pakistani floods [8, 27], the 2018 European heatwave [24, 28, 29], the 2020 record breaking Siberian heatwave [5] and the record shattering 2021 Pacific northwest heatwave [30–32]. From a statistical perspective, Screen & Simmonds [33] showed that high amplitude Rossby waves assessed on monthly hemispheric mean meridional wind can be generally considered to be significantly related to local weather extremes. Coumou *et al* [34] showed that heat extremes can become globally synchronized when hemispheric synoptic scale wave patterns on roughly monthly timescales emerge, while Wang *et al* [14] identified the impact of circumglobal patterns on local rainfall extremes. Recently, Kornhuber *et al* [7] found that CGTs assessed on weekly timescales significantly favor the emergence of concurrent heat extremes in specific hotspot regions across the mid-latitudes.

4. Quantifying the slow-moving dynamics of synchronized weather extremes in summer 2018

In summer 2018, the Northern Hemisphere extratropics experienced several heat and precipitation extremes [29, 35, 36] some of which coincided with a strongly meandering jet [37, 38] which was categorized as an amplified wave-7 pattern [24, 28] (also see figure 1).

In K19, wave patterns were identified by applying a fast Fourier transformation (FFT) on the 15 d mean of the mid-latitude meridional wind in the upper troposphere (300 mb) following the approach described in detail in earlier publications from a similar group of authors [10, 12, 15, 26, 34]. This approach has several advantages as it characterizes the hemispheric flow through four interpretable metrics, which can be linked to linear theory without effort: wavenumber, wave-amplitude, phase position and phase speed (note that in K19 phase speeds are quantified based on daily fields before a 15 d running mean is applied, they are not based on a visual analysis as suggested by JR). To visualize the temporal evolution of this pattern and its latitudinal variation a Hovmöller diagram of the 15 d running mean meridional winds in summer 2018 was generated (figure 2(b) in K19) which illustrates the emergence of an amplified ridge-through pattern with the strongest signals over Eurasia, coinciding in time and space with the most severe heat and rainfall extremes during that summer.

5. Quantitative methods surpass visual interpretations

In his comment to K19, JR remarks that 'figure 2(b) of K19 is actually a time-filtered version of the usually employed Hovmöller diagram, which is normally based on unfiltered meridional wind'. In contrast to JR's assertion, we want to highlight that Hovmöller diagrams are not limited to a specific time scale or investigated variable. Numerous examples and applications exist in which illustration the temporal evolution over one spatial dimension of a given variable helps in gaining new insights (see e.g. www.e-education.psu.edu/meteo820/node/549 for numerous examples of peer-reviewed research using Hovmöller diagrams on timescales from daily running means, months to years). JR continues to suggest that applying a 15 d running mean for wave amplitude detection was not clearly communicated in K19 'The result of this low-pass filtering operation, which is not explicitly mentioned in K19, is shown in figure 1(b)'. It is important to note that the 15 d mean

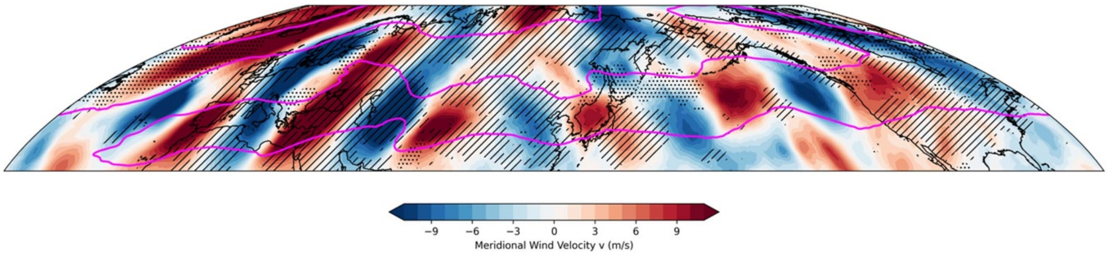

Figure 1. A wave-7 circumglobal teleconnection in summer 2018 guided by the mid-latitudinal jet. Filled contours show the 15 d mean 300 mb meridional winds centered around the 1st of July in the Northern Hemisphere (25 deg.–75 deg. North), magenta line contours show the 15 d mean 10 m s^{-1} contour of the 300 mb zonal winds. Hatching and stippling show hot (above 1.2 deg. K) and cold (below 0.5 deg. K) based on a 15 d mean of the daily mean temperature anomalies relative to 1981–2010 day in year averages. Concurrent temperature extremes emerge between the ridges formed by the CGT. Continental boundaries are shown in black.

perspective is mentioned several times throughout the main manuscript and methods section. All methods including the application of a 15 d running mean follow the approaches of earlier peer-reviewed publications from the same group of authors (see above).

While a visual analysis of Hovmöller diagrams might be common practice in some communities, we want to stress that caution is advised when using these insights for physical interpretation. Quantitative methods (as applied for K19 and shown in figures 2(c)–(e)) should always be the preferred approach where possible. Wave event, phase speed and position were based on the FFT and did not rely on the visual interpretation of figure 2(b). Naturally, a 6 h Hovmöller diagram (a nitpicky reader might ask JR, why did he not go for hourly data?) allows for different insights compared to a 15 d running mean illustration. While the former allows for the investigation of small-scale dynamics and mechanisms as well as localized turbulent features, a time filtered perspective can expose persistent features and allows for a mathematical description based on linear theory.

Most importantly, we want to highlight that a natural visual interpretation in the complementary perspective of the 6 h Hovmöller diagram shown by JR (figure 1(a)) comes to the same conclusion as K19: the emergence and persistence of quasi-stationary waves in its preferred wave-7 CGT phase position, overlaid with eastward migrating high frequency patterns (which are removed by the 15 d running mean in K19). Thus, while JR claims that the approach by K19 'displayed an unrealistic and incomplete representation of the hemispheric Rossby wave pattern', we assert that figure 1(a) in JR serves as a confirmation that indeed stationary eddies were present over a wide range of the Northern Hemisphere mid-latitudes for one to two weeks, which are thus not an artifact of a time filter.

More generally, while 2-dimensional representation of a complex system like the atmosphere will be incomplete, there is nothing 'unrealistic', or 'misleading' (as stated elsewhere in JR) about the Hovmöller figure shown in K19: as with any data-analysis exercise, the figures require an interpretation which is in accordance with the data processing and under consideration of the context provided. This also relates to JRs statements on group velocity vs phase velocity, where a visual interpretation and manually drawn arrows might not be an appropriate method to gain useful insights in this case.

6. Circumglobal teleconections amid the weather–climate schism

Various metrics exist that allow for characterization of the state of the mid latitudinal flow. These range from local blocking indicators [39], to longitudinally extended wave packages [40], to waviness metrics [41]. Each of these diagnostics are motivated by certain spatial and temporal scales that allow for statements on different physical processes. Naturally, their choice and interpretation should be informed by their advantages and limitations. K19 shows the existence of a preferred phase for a wave-7 pattern that is quantified on a hemispheric basis. An amplified wave-7 in its preferred phase position was detected during the synchronous weather extremes of summer 2018 and can be considered a dominant driver in their maintenance and emergence. Complementary perspectives include local blocking patterns, a stationary wave package over Eurasia, a double jet pattern [42] or a positive summer NAO [28]. In a recent study by Rousi *et al* [29] (Kornhuber and Coumou are co-authors), these perspectives were comprehensively summarized (notably also featuring a daily Hovmöller plot in figure 4, which is discussed to a large extent).

We want to conclude that the complex character of the midlatitude circulation and its response to global warming will not be captured and understood by using a single metric or time-scale alone. Multiple perspectives and approaches from dynamical meteorology, climate and weather research are needed which will help to produce a comprehensive picture through their diversity. In a recent essay Randall & Emmanuel [43] note the unfortunate separation of two distinct communities raised on 'Weather' and

'Climate', respectively, whose research centers around the atmospheric circulation but tends to use very distinct methods and scales: observations from station data, daily to sub-daily timescales, meso- to synoptic scales (weather) vs reanalysis, model data, long term means and synoptic to global scales (climate). Overcoming the challenging and pressing questions associated with the atmosphere-dynamical response to climate change will require expertise from all related fields and a scientific discussion around different hypotheses and their supporting evidence. Given the rapid rise in extremes—and our limited understanding of the underlying dynamical processes—it is essential to have this scientific debate, but this does not benefit from careless framing of specific contributions as 'unrealistic' or 'misleading'.

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