

Geophysical Research Letters

RESEARCH LETTER

10.1029/2020GL091452

Key Points:

- Recurrent Rossby wave packets significantly alter (lengthen or shorten) the persistence of both wet and dry spells in the extratropics
- They lengthen or shorten dry (wet) spells through the recurrent formation of ridges (troughs) in the same area
- Recurrence of transient Rossby waves should be considered as a key dynamical mechanism for fostering persistent surface weather

Supporting Information:

- Supporting Information S1

Correspondence to:

S. M. Ali,
mubashshir.ali@giub.unibe.ch

Citation:

Ali, S. M., Martius, O., & Röthlisberger, M. (2021). Recurrent Rossby wave packets modulate the persistence of dry and wet spells across the globe. *Geophysical Research Letters*, 48, e2020GL091452. <https://doi.org/10.1029/2020GL091452>

Received 30 OCT 2020

Accepted 6 JAN 2021

Recurrent Rossby Wave Packets Modulate the Persistence of Dry and Wet Spells Across the Globe

S. Mubashshir Ali¹ , Olivia Martius^{1,2} , and Matthias Röthlisberger³ 

¹Oeschger Centre for Climate Change Research and Institute of Geography, University of Bern, Bern, Switzerland,

²Mobilair Lab for Natural Risks, University of Bern, Bern, Switzerland, ³Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland

Abstract Persistent dry and wet spells can arise from stationary weather situations or recurrent flow patterns and result in significant socio-economic impacts. Here, we study the effects of recurrent synoptic-scale transient Rossby wave packets (RRWPs) on the persistence of dry and wet spells using the ERA-Interim reanalysis data. RRWPs significantly alter (decrease and increase) dry and wet spell persistence across the globe. Spatial patterns of statistically significant links between RRWPs and spell durations arise from the superposition of a zonally symmetric component and a wave-like component that is modulated by local factors such as orography and the position relative to major moisture sources. The zonally symmetric component is apparent during the Northern Hemisphere winter and dominates the Southern Hemisphere signal in winter and summer. The wave-like component appears primarily in the Northern Hemisphere, changes its wavenumber with the season and is thus, conceivably related to stationary wave dynamics.

Plain Language Summary Unchanged weather conditions over a prolonged period (persistent weather) can lead to adverse conditions for example, in agriculture. Traditionally, such weather conditions are understood to arise from slow-moving (i.e., “stationary”) weather systems. In this study, we illustrate an alternative, “non-stationary” atmospheric flow configuration, which can cause such persistent weather by the repeated formation (recurrence) of troughs and ridges in the same areas. The upper-level atmospheric waves, which influence our daily weather, govern this process. We show two example cases, where recurrence leads to persistent dry or wet conditions. By analyzing over 35 years of data, we find such wave recurrence to be statistically relevant for persistent dry and wet conditions. For many land areas of both the Northern and the Southern Hemisphere, increased or reduced persistence of dry and wet conditions are related to the recurrent upper-level waves.

1. Introduction

Persistent extreme surface weather events pose a threat to food security, health, livelihood, and property (Kornhuber et al., 2020; Raymond et al., 2020; Rudd et al., 2020; Sivakumar, 2018). Persistent dry conditions can lead to droughts and exacerbate wildfires, whereas persistent wet conditions can lead to flooding. On multi-day to sub-seasonal timescales, persistent conditions may offer windows of high predictability but remain challenging for numerical weather forecast models (Ferranti et al., 2015; Matsueda & Palmer, 2018). Therefore, fundamental process understanding is essential for improving forecasts of such events (Quandt et al., 2017; Webster et al., 2011), and to reduce uncertainties in the future climate projections.

Persistent dry and wet spells are often related to slow-moving or stationary weather systems. Quasi-stationary blocking anticyclones (e.g., Rex, 1950; Pelly & Hoskins, 2003), are associated with subsidence, and thus, they often exhibit clear-sky conditions in their central and downstream part. Subsidence and increased shortwave radiation at the surface leads to hot and dry surface anomalies (e.g., Li et al., 2020; Pfahl & Wernli, 2012; Quinting et al., 2018; Xu et al., 2020; Zschenderlein et al., 2020). The persistence of the blocking anticyclones can then result in long-lasting heatwaves and persistent dry spells (Fang & Lu, 2020; Röthlisberger & Martius, 2019). Persistent wet spells can arise as a result of slow-moving and stalling tropical and extratropical cyclones (e.g., Risser & Wehner, 2017; Rhodes, 2017), persistent monsoon circulation patterns (e.g., Y. Fang et al., 2012), stationary cut-off lows (e.g., Lenggenhager et al., 2019), and as a result of an eastward extension of the jet over the Atlantic (e.g., Blackburn et al., 2008; Schaller et al., 2016). Quasi-stationary

waves, in particular those spanning an entire Hemisphere, can also be associated with both persistent dry and wet spells around the globe (Coumou et al., 2014; Kornhuber et al., 2016; Stadtherr et al., 2016; Wolf et al., 2018). However, besides stationary drivers, a number of studies have identified recurrent (rather than stationary) large-scale circulation as a cause for persistent surface weather (e.g., Drouard & Woollings, 2018; Michelangeli et al., 1995).

Recurrence of transient weather systems in the same area on sub-seasonal timescales can be associated with persistent extreme surface temperature conditions. A statistically significant link exists between recurrent Rossby wave packets (RRWPs) and the persistence of winter-cold and summer-hot spells over large areas in the Northern Hemisphere midlatitudes (Röthlisberger et al., 2019). Such RRWP events are characterized by the repeated passage of transient synoptic-scale RRWPs in the same phase at the same longitude. Both recurrent ridging or troughing due to RRWPs can result in persistent hot and cold spells (Röthlisberger et al., 2019). A few notable examples of RRWPs inducing persistent surface weather are the 1994 Central European heat wave (Röthlisberger et al., 2019), the anomalous Northern Hemisphere 2013–2014 winter (Davies, 2015; Wolter et al., 2015), and flooding in the Southern Alpine region in fall 1993 (Barton et al., 2016).

Röthlisberger et al. (2019) quantified the climatological effect of RRWPs on the duration of temperature spells in the Northern Hemisphere, while the other studies cited above present case study-based evidence for a link between RRWPs and persistent wet and dry spells. However, a systematic and global evaluation of the effect of RRWPs on the persistence of dry and wet spells is so far missing. The purpose of this paper is twofold: First, we aim to identify regions where the persistence of these spell types is significantly altered by RRWPs. Second, we discuss the physical processes linking the upper-level RRWPs to persistent wet and dry surface conditions based on example cases.

2. Data and Method

This study uses ERA-Interim (ERA-I) reanalysis data (Dee et al., 2011) on a 1° by 1° spatial resolution for the period 1980–2016. Atmospheric fields are used at 6-hourly temporal resolution. Atmospheric blocking is identified based on upper-level negative potential vorticity (PV) anomalies as in Schwierz et al. (2004), but with slight modifications (Rohrer et al., 2018). Daily aggregated precipitation data is used for the identification of dry and wet spells at each grid point. Days with accumulations below (exceeding) 1 mm are classified as dry (wet) days. Spells separated by a one-day gap are merged into one continuous spell. From the resulting sets of dry and wet spells, all spells lasting less than 5 days are discarded, as we motivate our study from an impacts point of view. This procedure results in a set of n_g spells at each grid point g , each with durations $D_{g,1}, \dots, D_{g,n_g}$ (Figures S1 and S3).

We assess the effect of RRWPs on dry (wet) spell durations in both the hemispheres, separately for extended summer (May–October, MJJASO) and extended winter (November–April, NDJFMA), using a Weibull regression model following Röthlisberger et al. (2019). The notation used here is consistent with theirs. They introduced a metric “ R ” as a simple measure of RRWP strength derived from Hovmöller (time-longitude) diagrams of instantaneous meridionally averaged (35°N – 65°N) meridional wind at 250 hPa (V_{250}). The R -metric is in essence the envelope of a time (15–days running mean) and wavenumber (WN) filtered (WN = 4 to WN = 15) V_{250} field (see Röthlisberger et al., 2019 for more details). We have computed this metric also for the Southern Hemisphere (SH) from meridionally averaged (35°S – 65°S) V_{250} . We used the respective R as a covariate in a Weibull regression model fitted separately to dry and wet spell durations at each grid point poleward of 20°N and 20°S , respectively. Only grid-points that have at least 40 spells in the respective season during 1980–2016 are considered. The Weibull model is more complex compared to the standard Gaussian linear model but, it allows us to assess changes in all quantiles of the modeled spell duration distribution per unit increase in each covariate (Supplementary Material in Röthlisberger et al., 2019). Thus, it is possible to assess the effect of RRWPs via the covariate R on the entire distribution of spell durations. While the statistical analysis can reveal covariability between R and the spell durations, the causality in our statistical arguments is based on the case studies cited above and shown later here and in the Supplementary Material.

The Weibull model is fitted at each grid point and is only briefly introduced here for an arbitrary grid point g . First, a representative value of $R(\bar{R}_{\lambda_g, i})$ is assigned to each spell i occurring at this grid point (with longitude

λ_g), which quantifies how recurrent the synoptic scale waves are in the 60° longitudinal sector centered on λ_g during the lifetime of a spell i (Equation 1). To calculate the $\tilde{R}_{\lambda_g,i}$, the raw R -metric, which is a function of longitude and time, is longitudinally averaged within the 60° longitudinal sector centered on λ_g for each time step. Then, the representative R value $\tilde{R}_{\lambda_g,i}$ of spell i is computed as the median of these longitudinally averaged R values $R_{lon}(\lambda, t)$ during the lifetime of the spell (from t^{start} till t^{end}):

$$\tilde{R}_{\lambda_g,i} = \text{median} \left\{ R_{lon}(\lambda, t), t = t_{g,i}^{\text{start}}, \dots, t_{g,i}^{\text{end}} \right\}, \quad (1)$$

The Weibull regression model fitted to the spell durations $D_{g,1}, \dots, D_{g,n_g}$ at each grid point g is given by:

$$\ln(D_{g,i}) = \alpha_{0,g} + \alpha_{1,g} \tilde{R}_{\lambda_g,i} + \sum_{j=2}^6 \alpha_{j,g} m_j(t_{g,i}^{\text{start}}) + \sigma_g \epsilon_{g,i}; i = 1, \dots, n_g, \quad (2)$$

where $\alpha_{0,g}, \dots, \alpha_{6,g}$ are the regression coefficients, $\epsilon_{g,1}, \dots, \epsilon_{g,n_g}$ are the error terms following the standard extreme minimum value distribution and $\sigma_g > 0$ is a scale parameter. Additionally, m_2, \dots, m_6 are covariates representing dummy variables for each month (DJFMA/JJASO) to account for seasonal variations in spell durations and R (Röthlisberger et al., 2019). The intercept $\alpha_{0,g}$ represents the starting month (November/May). Fitting the model to spell durations at each grid point then results in maps of regression coefficients $\alpha_{j,g}$, $j = 0, \dots, 6$, where $\alpha_{1,g}$ represents the effect of \tilde{R} on the spell durations. The null hypothesis examined here is that RRWPs have no effect on the duration of dry and wet spells, which is rejected at a grid point g if $\alpha_{1,g}$ is significantly different from zero. Two-sided significant departures of $\alpha_{1,g}$ from zero are identified as in Zhang (2016) at a significance level of 0.025 and 0.975.

Hereafter, we present the exponentiated regression coefficient $\exp(\alpha_{1,g})$ called “acceleration factor” (AF) in survival analysis applications (e.g., Hosmer et al., 2008; Zhang, 2016). The AF $\exp(\alpha_{1,g})$ depicts the factor by which all quantiles of the spell duration D_g at a grid point g changes per unit increase in the covariate $\tilde{R}_{\lambda_g,i}$ (Hosmer et al., 2008). Here, we use the AFs to identify statistically significant links between RRWPs and spell durations, and therefore focus on regions where AF is significantly larger or smaller than 1, and not on the AF values themselves. Regions with $\text{AF} > 1$ ($\text{AF} < 1$) experience significantly increased (decreased) spell durations with an increasing R value, that is, during RRWP conditions. We tested the sensitivity of our results to changes in the minimum spell duration and the gap duration parameters. We found consistent AF patterns for the minimum spell durations of 4, 5, and 6 days with the respective gap duration of 0 and 1 day. We also test the goodness-of-fit of our model with an Anderson-Darling test at significance level 0.01, exactly as in Röthlisberger et al. (2019).

3. Results

3.1. Examples of Persistent Wet and Dry Spells during RRWPs

Two case studies serve to introduce key concepts of this study: a persistent wet episode in Spain, and a persistent dry episode in Brazil. During April–May 1983, persistent wet conditions over the Iberian Peninsula led to a 35-days long wet spell at a grid-point in western Spain (red cross in Figure 1a). The daily precipitation accumulation exceeded the local 90th percentile for 11 days during this spell. While blocking was present over south Greenland during the first 10 days of the spell (Figures 1b and 3a) a series of additional (and clearly distinct) transient wave packets moved across the Atlantic during the subsequent three weeks, which resulted in continuously high R values between 60°W and 30°E (Figure 1b). Recurrent flow conditions over the eastern Atlantic (Figure 1b) resulted in repeated advection of moist air to north-western Spain. Concurrently, precipitation anomalies were also present upstream over the Atlantic basin and downstream in the Mediterranean, all of which were associated with a wave pattern over the Atlantic basin (Figures 1b and 3a), and consequently high R values. Note that no circumglobal wave pattern was present. The negative precipitation anomalies were co-located with the ridges and the positive precipitation anomalies were located downstream of the trough axes (Figure 3a). Interestingly, during this period, atmospheric blocks were also frequent over the Gulf of Alaska (Figure 3a).

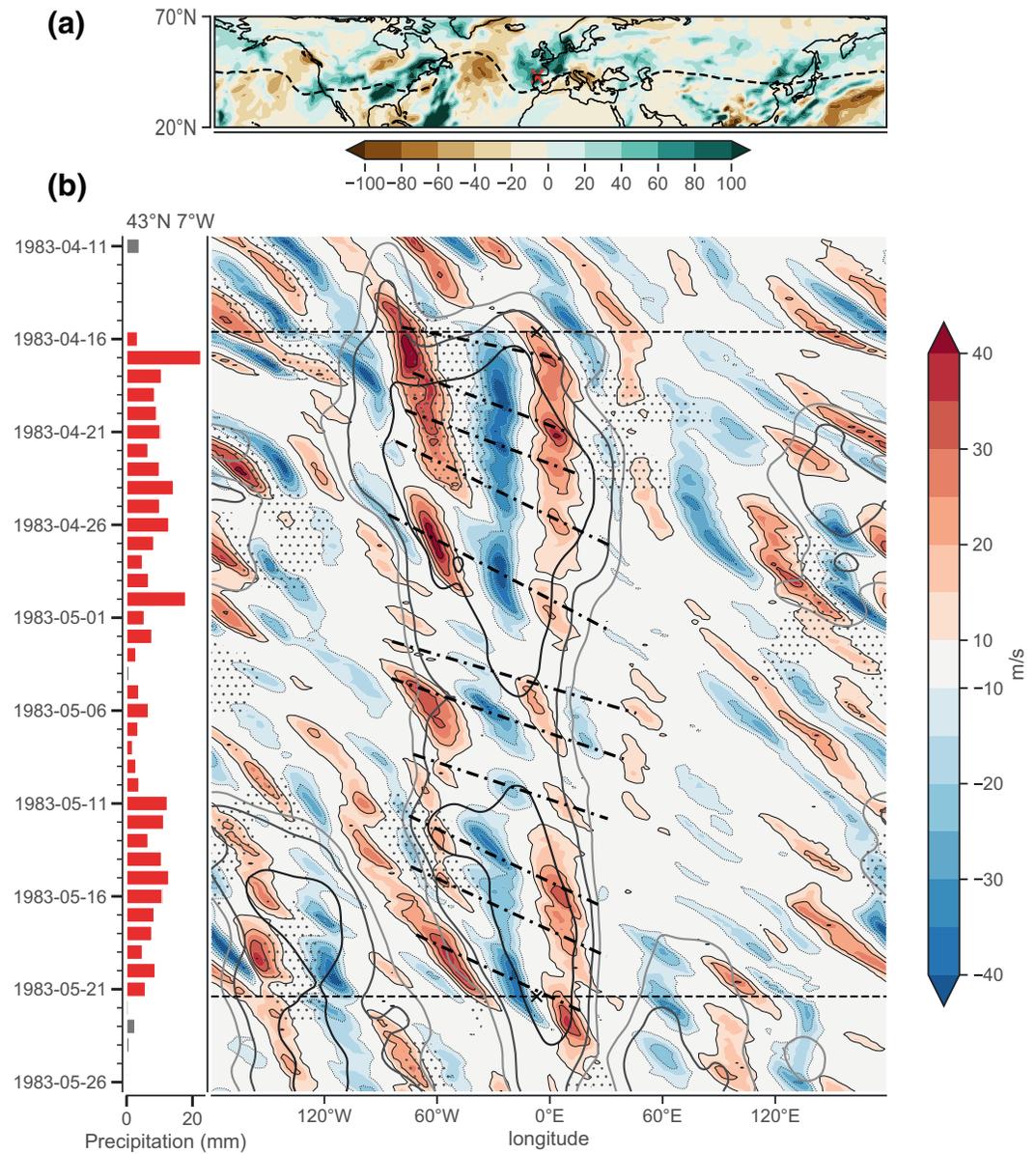


Figure 1. An example wet spell during April 16, 1983 till May 21, 1983. (a) Anomalous daily precipitation (mm) compared to ERA-I daily climatology (1979–2018) aggregated for the spell duration. Dashed contour shows 2PVU at the 330 K isentropic averaged for the spell duration. (b) Bars show aggregated daily precipitation at location “X” (43°N, 7°W) in (a), red when precipitation is in the spell period and above 1 mm threshold, else gray. The Hovmöller diagram in (b) shows 35°N–65°N averaged meridional wind at 250 hPa. Black dotted lines in (b) mark the onset and end of the spell at “x” in (a). Gray contours show R values of 8, 10, and 14 m/s. Stippling depicts longitudes at which at least one grid point in 20°N–70°N featured an atmospheric block while the dash-dotted lines indicate the approximate longitude–time trajectory of the RRWP (i.e., group propagation).

In November 1985, recurrent Rossby waves were associated with persistent dry conditions over São Paulo, Brazil, and surroundings (Figure 2). A series of recurrent and non-stationary RRWPs moved across the Southern Pacific in quick succession. It resulted in recurrent ridging over São Paulo (Hovmöller plot in Figure 2b). The wave pattern is also evident in the PV composite for this period (Figure 3b). Interestingly, blocking was not present over the São Paulo region, but two blocks appear over the Indian Ocean (south of Australia), one in the beginning and one toward the end of this period. There is an indication of anticyclonic wave breaking happening upstream of Patagonia in the Southern Pacific Ocean (Figure 3b).

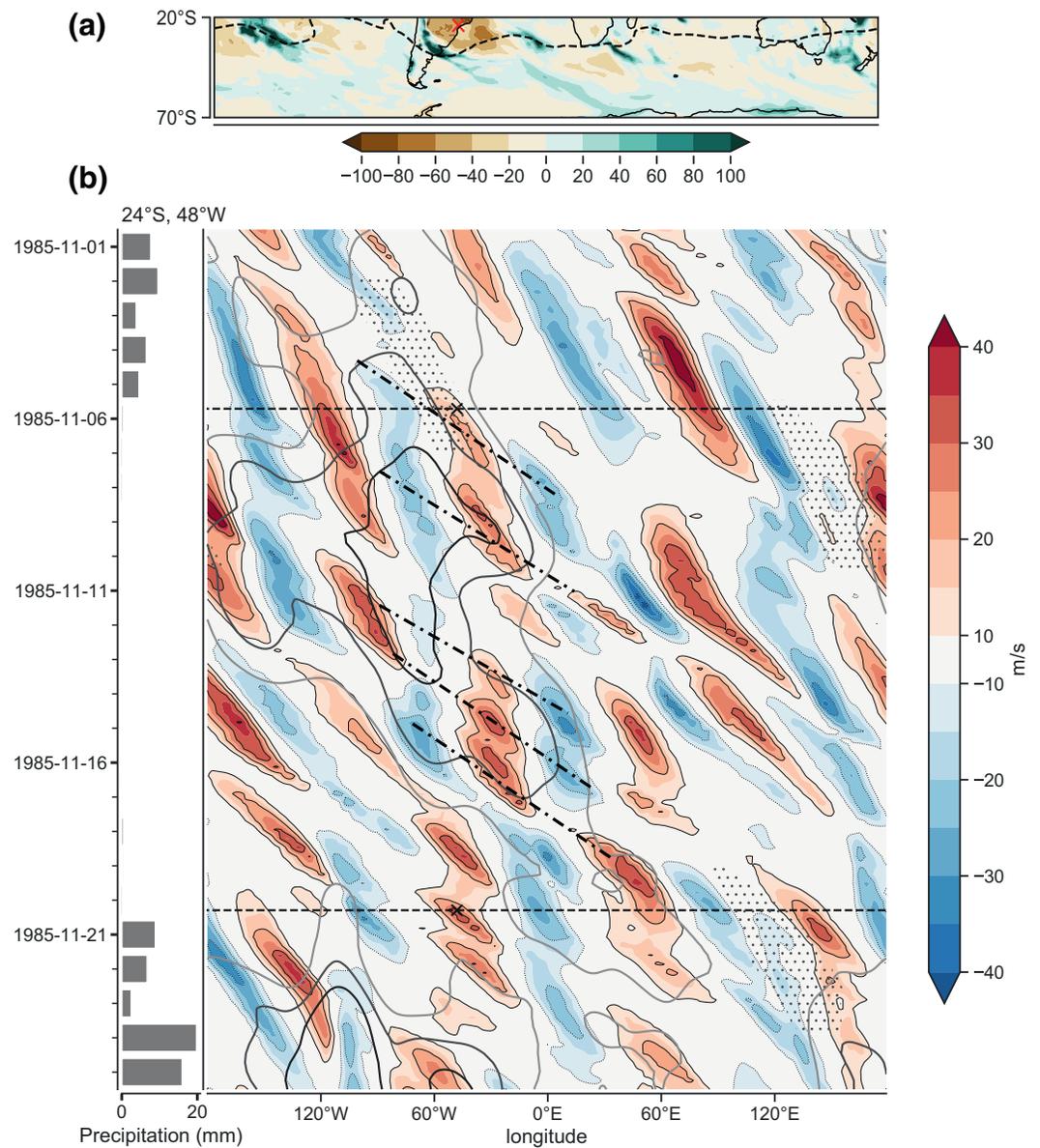


Figure 2. (a) and (b) same as Figure 1 but for a dry spell event at 24°S, 48°W (Brazil) during November 6, 1985 till November 20, 1985. Dashed contour in (a) shows -2PVU at the 345 K isentropic averaged for the spell duration. The Hovmöller diagram and the R-metric has been computed for 35°S–65°S. Gray contours in (b) show R values of 8, 10, and 12 m/s.

Two additional case studies are included in the Supplementary material (Figures S5 and S7). These case studies clearly illustrate that besides blocking, recurrent amplification of troughs and ridges in the same geographical areas can also foster persistent dry and wet spells on subseasonal timescales. In the remainder of this study, we, therefore, quantify the effect of RRWPs on the persistence of dry and wet spells.

3.2. Rossby Wave Recurrence Associated with Dry Spells

Next, we present AF fields and begin with dry spells in the Northern Hemisphere. Recall that $AF > 1$ ($AF < 1$) indicates a significant increase (decrease) of spell durations during RRWPs (i.e., for large values of R). Figures 4a and 4b show that RRWPs significantly affect the Northern Hemisphere dry spell durations during both the extended summer (MJJASO) and the winter (NDJFMA) seasons. However, this effect varies

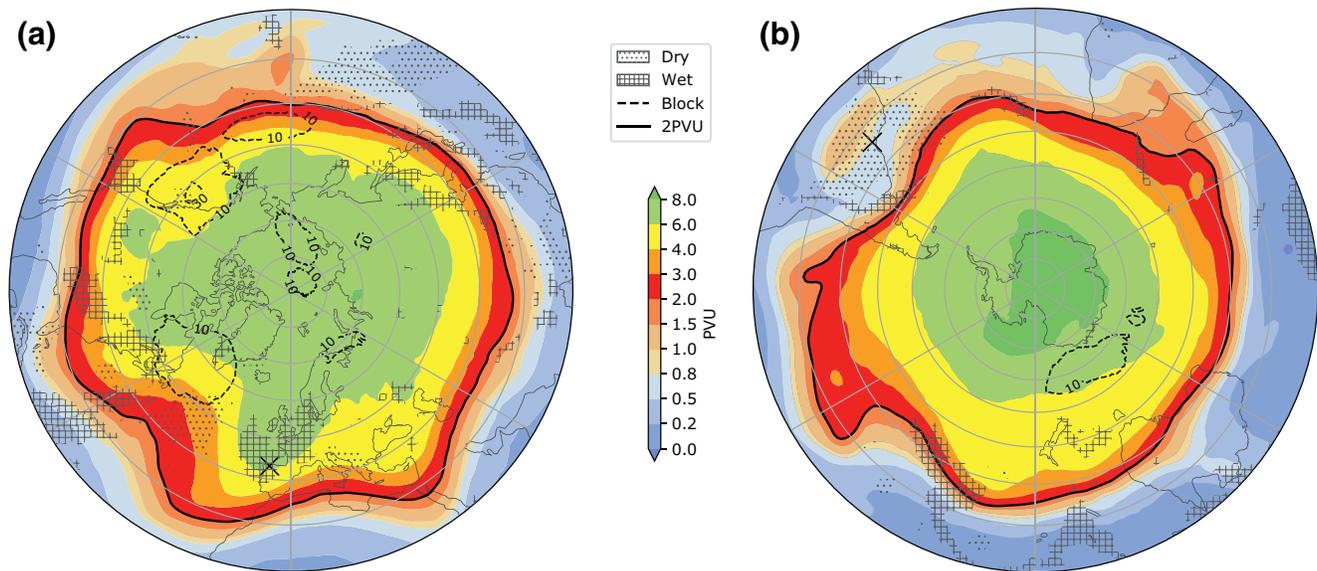


Figure 3. (a) PV at the 335K isentropic averaged over the duration of wet spell shown in Figure 1. (b) Same as in (a) but at the 345 K isentropic for the dry spell examined in Figure 2. Daily precipitation anomalies aggregated for the spell duration exceeding ± 40 mm are indicated by the corresponding hatches (see legend). Dashed contours show blocking frequencies in percent. The “X” indicates the grid points for which the precipitation time series are shown in panels (b) of Figures 1 and 2.

in sign depending on the region and the season. A positive effect of RRWPs on MJJASO dry spell durations is, for example, apparent in North America, central Europe, and eastern China (Figure 4a), while a negative effect is evident, for example, over eastern Iberia, western Greenland, and numerous subtropical regions. Moreover, during MJJASO, some indication of a wave-like pattern is evident, in particular between 120°W and 60°E in the extratropics. During the NDJFMA (Figure 4b), significant Northern Hemisphere AF patterns have clear latitudinal structure, with widespread $\text{AF} < 1$ in the subtropics and the Arctic. Moreover, the mid-latitudes again feature a rather wave-like AF pattern (approximately WN 4) in the extratropics, in particular over the US and the Atlantic. Note that in both seasons widespread $\text{AF} > 1$ regions are present in the mid-latitudes, but only some parts of the US have $\text{AFs} > 1$ in both seasons (Figures 4a and 4b).

Moving on to the SH dry spells, we find that RRWPs significantly affect dry spell durations during MJJASO and NDJFMA, albeit more strongly during the latter (Figure 4). During NDJFMA, $\text{AFs} > 1$ are found over parts of subtropical South America, south-eastern Australia, and New Zealand, and $\text{AFs} < 1$ over parts of Patagonia, southern Africa, and northern and central Australia. Moreover, the majority of the $\text{AFs} > 1$ are present in the mid-latitudes. During MJJASO, however, the AF field shows a patchy structure, with coherent regions of statistically significant $\text{AFs} (< 1)$ primarily in the subtropics and along the Antarctic coast.

3.3. Rossby Wave Recurrence Associated with Wet Spells

Similarly, for wet spell durations, the effect of RRWPs is dependent on the region and the season (Figure 5). In the NH, there are coherent regions with significantly longer wet spells during MJJASO in western Europe (France, Iberia) and western Russia (Figure 5a). In contrast to AFs for dry spells, for wet spells there are only few North American grid points with AFs significantly different from zero (cf. Figures 4a and 5a). During NDJFMA, RRWPs are associated with longer wet spells mainly over eastern Europe and the Mediterranean (Figure 5b), whereas large and reasonably coherent regions of $\text{AFs} < 1$ appear over the eastern North Atlantic (including Ireland, the UK) as well as over North-western Russia. Furthermore, no latitudinal structure in the wet-spell AFs is apparent in the Northern Hemisphere. However, note that many high-latitude and subtropical areas are excluded from this analysis due to too few wet spells.

In contrast, in the SH (Figure 5), the AF fields exhibit a clear latitudinal structure that is evident in both seasons. The AF patterns indicate an increase of wet spell durations associated with RRWPs between 30°S

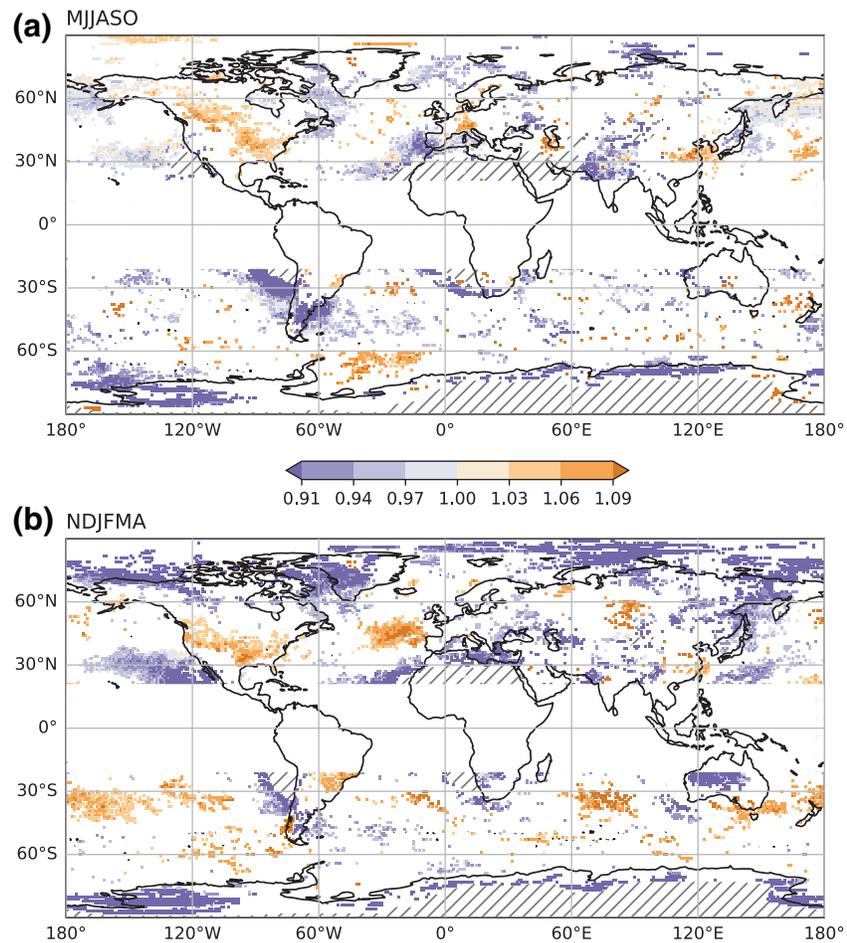


Figure 4. Statistically significant acceleration factors for (a) MJJASO and (b) NDJFMA dry spells. Northern Hemisphere (Southern Hemisphere) grid points show AFs from a Weibull model with the NH (SH) R-metric as a covariate, respectively. AFs between 20°S and 20°N are masked out to visually separate AFs for Northern (Southern) Hemisphere R. Lined hatches show areas excluded from the regression model due to too few spells. Stippling denotes areas where the spell durations do not fit our Weibull model based on an Anderson-Darling test at significance level 0.01.

and 50°S, and a decrease of wet spell durations associated with RRWPs south of 50°S. In particular, positive AF regions are apparent for both seasons over subtropical South America and parts of New Zealand.

4. Discussion

Our results demonstrate that recurrence of transient Rossby waves significantly affects the persistence of dry and wet spells. However, its effect can take either sign; it can both increase or decrease wet and dry spells.

Most regions where RRWPs are associated with a decrease in spell durations are regions where persistence is large climatologically, for example, in the subtropics and the Arctic for dry spells, and in the storm track regions for wet spells (for median spell durations see Figures S2 and S4). This implies that the recurrent troughs and ridges can interrupt wet and dry periods in these regions and reduce persistence.

The AF patterns for wet and dry spells arise from a combination of three components: a zonally symmetric component, a wave-like component, and a local component. The zonally symmetric component is most coherent in winter. It is characterized by distinct latitudinal bands in the AFs: with increased wet spell persistence on the equatorward side of the storm tracks (most evident in winter for NH Pacific and SH storm

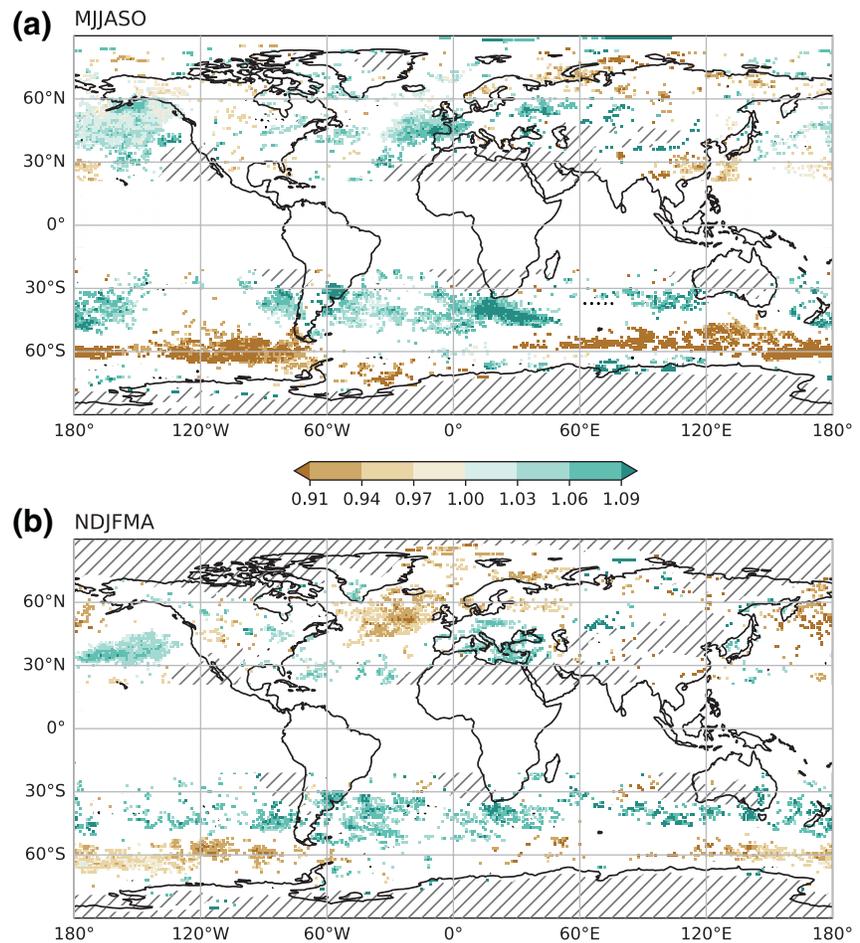


Figure 5. Same as Figure 4 but for (a) MJJASO and (b) NDJFMA wet spells.

tracks), and reduced wet spell persistence in the central part of the storm tracks (both for NH Pacific and Atlantic, and SH storm tracks in winter). Furthermore, it features increased dry spell persistence in the parts of North Atlantic (NDJFMA) and the South Atlantic (MJJASO) storm tracks and reduced dry spell persistence in the subtropics and Arctic.

The zonally symmetric part can be understood by recalling that RRWPs are highly amplified flow situations. Hence, they lead to increased moisture transport into the polar regions and frequent RWB. The increased polar moisture transport can interrupt dry spells (e.g., Ali & Pithan, 2020; Papritz & Dunn-Sigouin, 2020; Uotila et al., 2013). Similarly, frequent RWB can foster unusually persistent wet conditions on the equatorward flank of the storm tracks (e.g., De Vries, 2020; De Vries et al., 2013) and interrupt dry spells by triggering convection (e.g., Funatsu & Waugh, 2008; McTaggart-Cowan et al., 2013). Recurrent ridging in the central part of the storm tracks (which are climatologically very wet regions) can shorten wet spells there (Wernli & Schwierz, 2006). The zonally symmetric part has also been discussed in R othlisberger et al. (2019; their Figure 10a), but for persistent cold spells in winter.

The wave-like component in the extratropical AF fields is relevant for dry spells in the NH and is more evident during boreal winter (Figures 4 and 5b). A similar wave-like component has also been reported by R othlisberger et al. (2019; their Figure 10b) for NH hot spells during summer, having a wavenumber 6–7. However, there is no clear circumglobal wavenumber for the AF patterns of dry and wet spells. The presence of such a wave-like component in the AFs implies that the RRWPs occur in preferred phases, that is, the formation of troughs/ridges within RRWPs occurs in preferred geographical regions. In areas where RRWPs increase wet spell duration, potentially recurrent highly amplified upper-level troughs contribute to

frequent precipitation along their downstream flank via quasi-geostrophic lifting. For example, the wet spell case in Spain during April–May 1983 described before, where recurrent troughs were present just east of the Iberian west coast (e.g., Figures 1 and 3a). Similarly, in areas where RRWPs are associated with longer dry spell durations, potentially recurrent upper-level ridges ensure dry and stable conditions (e.g., Figures 2 and 3b). Moreover, the lack of such a wave signal in the SH extratropics and the wavenumber dependence on the season (change from WN4 in winter to WN6 in summer) suggests that the wave component in the AF fields is related to the stronger planetary waves in the NH that organize the transient eddies in preferred phases. However, note that the wave patterns should not be interpreted as occurring concomitantly and hence, as a circum-hemispheric wave. Although, such RRWPs might exist, but we cannot infer their presence from the AF patterns. It remains to be investigated to what extent this wave-like component in the AF field relates to Quasi Resonance Amplification, etc., (Kornhuber et al., 2017).

Finally, the intricacies of local effects such as orography and moisture availability also affect AF patterns. For example, the case study shown in Figures 1 and 3a illustrates a long-lasting wet spell that is conceivably also affected by local orography. Furthermore, moisture transport is typically from the ocean toward the land and cannot cross major mountain ranges. This implies that local geography (coastline, mountain ranges, etc.) play a role in determining whether a particular flow configuration is conducive to more/less persistent dry or wet spells.

5. Conclusions

Previously, mainly the stationary flow has been considered as an important driver of persistent weather conditions. Here, we demonstrate the importance of recurrent transient synoptic-scale RRWPs for persistent dry and wet conditions. RRWPs provide a non-stationary mechanism for modulating persistent surface weather. Röthlisberger et al. (2019) showed that RRWPs affect Northern Hemisphere temperature spells. Here, we demonstrate that RRWPs also significantly affect the duration of dry and wet spells globally by significantly shortening or extending the persistent dry/wet conditions. Spatial patterns of statistically significant regression coefficients feature superimposed components, a zonally symmetric component, and a wave-like component that are modulated by local effects, presumably arising from the local geography, such as orography or the position relative to major moisture sources. The zonally symmetric component is apparent during the Northern Hemisphere winter and dominates the SH signal in both the seasons. The wave-like component appears primarily in the Northern Hemisphere, changes its wavenumber with the season, and is possibly related to stationary wave dynamics. Despite, the regional variations in modulating wet/dry spell persistence, our results demonstrate that RRWPs significantly alter the persistence of potentially high-impact surface weather; RRWPs should, therefore, be considered as an essential flow feature for understanding and predicting persistent sub-seasonal weather patterns.

Data Availability Statement

ERA-I reanalysis data (Dee et al., 2011), and open source Python packages (Hoyer & Hamman, 2017; Hunter, 2007; Kluver 2016) helped us immensely. Datasets created in this study are available from FAIR-aligned repository in the in-text data citation Ali (2020).

Acknowledgments

S. M. Ali and O. Martius acknowledge the Swiss National Science Foundation grant number 178751. M. Röthlisberger acknowledges the European Research Council (ERC) for funding (INTEXseas, grant agreement number 787652). We are also grateful to the two anonymous reviewers whose comments helped to improve this paper.

References

- Ali, S. M. (2020). *Dataset for Recurrent Rossby wave packets modulate the persistence of dry and wet spells across the globe (Version 1) [Data set]*. Geneva: Zenodo. <https://doi.org/10.5281/zenodo.4134145>
- Ali, S. M., & Pithan, F. (2020). Following moist intrusions into the Arctic using SHEBA observations in a Lagrangian perspective. *Quarterly Journal of the Royal Meteorological Society*, 146, 1–18. <https://doi.org/10.1002/qj.3859>
- Barton, Y., Giannakaki, P., von Waldow, H., Chevalier, C., Pfahl, S., & Martius, O. (2016). Clustering of regional-scale extreme precipitation events in southern Switzerland. *Monthly Weather Review*, 144(1), 347–369. <https://doi.org/10.1175/MWR-D-15-0205.1>
- Blackburn, M., Methven, J., & Roberts, N. (2008). Large-scale context for the UK floods in summer 2007. *Weather*, 63(9), 280–288. <https://doi.org/10.1002/wea.322>
- Coumou, D., Petoukhov, V., Rahmstorf, S., Petri, S., & Schellnhuber, H. J. (2014). Quasi-resonant circulation regimes and hemispheric synchronization of extreme weather in boreal summer. *Proceedings of the National Academy of Sciences*, 111(34), 12331–12336. <https://doi.org/10.1073/pnas.1412797111>
- Davies, H. C. (2015). Weather chains during the 2013/2014 winter and their significance for seasonal prediction. *Nature Geoscience*, 8(11), 833–837. <https://doi.org/10.1038/ngeo2561>

- De Vries, A. J. (2020). A global climatological perspective on the importance of Rossby wave breaking and intense moisture transport for extreme precipitation events. *Weather Climate Dynamics Discussion*. [pre-print]. <https://doi.org/10.5194/wcd-2020-44>
- De Vries, A. J., Tyrlis, E., Edry, D., Krichak, S. O., Steil, B., & Lelieveld, J. (2013). Extreme precipitation events in the Middle East: Dynamics of the active Red Sea Trough. *Journal of Geophysical Research: Atmosphere*, *118*, 7087–7108. <https://doi.org/10.1002/jgrd.50569>
- Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. <https://doi.org/10.1002/qj.828>
- Drouard, M., & Woollings, T. (2018). Contrasting mechanisms of summer blocking over Western Eurasia. *Geophysical Research Letters*, *45*(21), 12040–12048. <https://doi.org/10.1029/2018GL079894>
- Fang, Y., Chen, W., & Zhou, W. (2012). Analysis of the role played by circulation in the persistent precipitation over South China in June 2010. *Advances in Atmospheric Sciences*, *29*(4), 769–781. <https://doi.org/10.1007/s00376-012-2018-7>
- Fang, B., & Lu, M. (2020). Heatwave and blocking in the Northeastern Asia: Occurrence, variability, and association. *Journal of Geophysical Research: Atmosphere*, *125*, e2019JD031627. <https://doi.org/10.1029/2019JD031627>
- Ferranti, L., Corti, S., & Janousek, M. (2015). Flow-dependent verification of the ECMWF ensemble over the Euro-Atlantic sector. *Quarterly Journal of the Royal Meteorological Society*, *141*, 916–924. <https://doi.org/10.1002/qj.2411>
- Funatsu, B. M., & Waugh, D. W. (2008). Connections between potential vorticity intrusions and convection in the eastern tropical Pacific. *Journal of Atmospheric Science*, *65*(3), 65987. <https://doi.org/10.1175/2007JAS2248.1>
- Hosmer, D. W., Lemeshow, S., & May, S. (2008). *Applied survival analysis* (2nd ed.) United States of America: Wiley Series in Probability and Statistics, John Wiley & Sons, Inc. ISBN: 9780471754992. <https://doi.org/10.1002/9780471754992>
- Hoyer, S., & Hamman, J. (2017). Xarray: N-D labeled arrays and datasets in Python. *Journal of Open Research Software*, *5*(1), 10. <http://doi.org/10.5334/jors.148>
- Hunter, J. D. (2007). Matplotlib: A 2D graphics environment. *Computing in Science & Engineering*, *9*(3), 90–95. <https://doi.org/10.1109/MCSE.2007.55>
- Kluyver, T., Ragan-Kelley, B., Pérez, F., Granger, B. E., Bussonnier, M., Frederic, J., et al. (2016). Jupyter notebooks—a publishing format for reproducible computational workflows. In *Elpub* (pp. 87–90). <https://doi.org/10.3233/978-1-61499-649-1-87>
- Kornhuber, K., Coumou, D., Vogel, E., Lesk, C., Donges, J. F., Lehmann, J., & Horton, R. M. (2020). Amplified Rossby waves enhance risk of concurrent heatwaves in major breadbasket regions. *Nature Climate Change*, *10*(1), 48–53. <https://doi.org/10.1038/s41558-019-0637-z>
- Kornhuber, K., Petoukhov, V., Karoly, D., Petri, S., Rahmstorf, S., & Coumou, D. (2017). Summertime planetary wave resonance in the Northern and Southern Hemispheres. *Journal of Climate*, *30*, 6133–6150. <http://journals.ametsoc.org/doi/10.1175/JCLI-D-16-0703.1>
- Kornhuber, K., Petoukhov, V., Petri, S., Rahmstorf, S., & Coumou, D. (2016). Evidence for wave resonance as a key mechanism for generating high-amplitude quasi-stationary waves in boreal summer. *Climate Dynamics*, *49*(5), 1961–1979. <https://doi.org/10.1007/s00382-016-3399-6>
- Lenggenhager, S., Croci-Maspoli, M., Brönnimann, S., & Martius, O. (2019). On the dynamical coupling between atmospheric blocks and heavy precipitation events: A discussion of the southern Alpine flood in October 2000. *Quarterly Journal of the Royal Meteorological Society*, *145*(719), 530–545. <https://doi.org/10.1002/qj.3449>
- Li, M., Luo, D., Yao, Y., & Zhong, L. (2020). Large-scale atmospheric circulation control of summer extreme hot events over China. *International Journal of Climatology*, *40*, 1456–1476. <https://doi.org/10.1002/joc.6279>
- Matsueda, M., & Palmer, T. N. (2018). Estimates of flow-dependent predictability of wintertime Euro-Atlantic weather regimes in medium-range forecasts. *Quarterly Journal of Royal Meteorological Society*, *144*, 1012–1027. <https://doi.org/10.1002/qj.3265>
- McTaggart-Cowan, R., Galarneau, T. J., Bosart, L. F., Moore, R. W., & Martius, O. (2013). A global climatology of baroclinically influenced tropical cyclogenesis. *Monthly Weather Review*, *141*, 1963–1989. <https://doi.org/10.1175/MWR-D-12-00186.1>
- Michelangeli, P.-A., Vautard, R., & Legras, B. (1995). Weather regimes: Recurrence and quasi stationarity. *Journal of Atmospheric Sciences*, *52*(8), 1237–1256. [https://doi.org/10.1175/1520-0469\(1995\)052<1237:WRRASQ>2.0.CO;2](https://doi.org/10.1175/1520-0469(1995)052<1237:WRRASQ>2.0.CO;2)
- Papritz, L., & Dunn-Sigouin, E. (2020). What configuration of the atmospheric circulation drives extreme net and total moisture transport into the Arctic? *Geophysical Research Letters*, *47*(17), e2020GL089769. <https://doi.org/10.1029/2020GL089769>
- Pelly, J. L., & Hoskins, B. J. (2003). A new perspective on blocking. *Journal of the Atmospheric Sciences*, *60*(5), 743–755. [https://doi.org/10.1175/1520-0469\(2003\)060<0743:ANPOB>2.0.CO](https://doi.org/10.1175/1520-0469(2003)060<0743:ANPOB>2.0.CO)
- Pfahl, S., & Wernli, H. (2012). Quantifying the relevance of atmospheric blocking for co-located temperature extremes in the Northern Hemisphere on (sub-)daily time scales. *Geophysical Research Letters*, *39*(12), 1–6. <https://doi.org/10.1029/2012GL052261>
- Quandt, L., Keller, J. H., Martius, O., & Jones, S. C. (2017). Forecast variability of the blocking system over Russia in summer 2010 and its impact on surface conditions. *Weather and Forecasting*, *32*, 61–82. <https://doi.org/10.1175/WAF-D-16-0065.1>
- Quinting, J. F., Parker, T. J., & Reeder, M. J. (2018). Two synoptic routes to subtropical heat waves as illustrated in the Brisbane region of Australia. *Geophysical Research Letters*, *45*, 10700–10708. <https://doi.org/10.1029/2018GL079261>
- Raymond, C., Horton, R. M., Zscheischler, J., Martius, O., Aghakouchak, A., Balch, J., et al. (2020). Understanding and managing connected extreme events. *Nature Climate Change*, *10*, 611–621. <https://doi.org/10.1038/s41558-020-0790-4>
- Rex, D. F. (1950). Blocking action in the middle troposphere and its effect upon regional climate. *Tellus*, *2*(4), 275–301. <https://doi.org/10.3402/tellusa.v2i4.8603>
- Rhodes, R. I. (2017). *Clustering and stalling of North Atlantic cyclones: The influence on precipitation in England and Wales*, Reading: University of Reading. <http://centaur.reading.ac.uk/77911/>
- Risser, M. D., & Wehner, M. F. (2017). Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. *Geophysical Research Letters*, *44*(24), 12457–12464. <https://doi.org/10.1002/2017GL075888>
- Rohrer, M., Brönnimann, S., Martius, O., Raible, C. C., Wild, M., & Compo, G. P. (2018). Representation of extratropical cyclones, blocking anticyclones, and alpine circulation types in multiple reanalyses and model simulations. *Journal of Climate*, *31*(8), 3009–3031. <https://doi.org/10.1175/JCLI-D-17-0350.1>
- Röthlisberger, M., Frossard, L., Bosart, L. F., Keyser, D., & Martius, O. (2019). Recurrent synoptic-scale Rossby wave patterns and their effect on the persistence of cold and hot spells. *Journal of Climate*, *32*(11), 3207–3226. <https://doi.org/10.1175/JCLI-D-18-0664.1>
- Röthlisberger, M., & Martius, O. (2019). Quantifying the local effect of northern Hemisphere atmospheric blocks on the persistence of summer hot and dry spells. *Geophysical Research Letters*, *46*(16), 10101–10111. <https://doi.org/10.1029/2019gl083745>
- Rudd, A. C., Kay, A. L., Wells, S. C., Aldridge, T., Cole, S. J., Kendon, E. J., & Stewart, E. J. (2020). Investigating potential future changes in surface water flooding hazard and impact. *Hydrological Processes*, *34*(1), 139–149. <https://doi.org/10.1002/hyp.13572>
- Schaller, N., Kay, A. L., Lamb, R., Massey, N. R., Van Oldenborgh, G. J., Otto, F. E. L., et al. (2016). Human influence on climate in the 2014 southern England winter floods and their impacts. *Nature Climate Change*, *6*(6), 627–634. <https://doi.org/10.1038/nclimate2927>

- Schwierz, C., Croci-Maspoli, M., & Davies, H. C. (2004). Perspicacious indicators of atmospheric blocking. *Geophysical Research Letters*, *31*, L06125. <https://doi.org/10.1029/2003GL019341>
- Sivakumar, M. V. (2018). Climate extremes and impacts on agriculture. *Agroclimatology: Linking Agriculture to Climate*, *60*, 621–647. <https://doi.org/10.2134/agronmonogr60.2018.0006>
- Stadtherr, L., Coumou, D., Petoukhov, V., Petri, S., & Rahmstorf, S. (2016). Record Balkan floods of 2014 linked to planetary wave resonance. *Science Advances*, *2*(4), 1–7. <https://doi.org/10.1126/sciadv.1501428>
- Uotila, P., Vihma, T., & Tsukernik, M. (2013). Close interactions between the Antarctic cyclone budget and large-scale atmospheric circulation. *Geophysical Research Letters*, *40*(12), 3237–3241. <https://doi.org/10.1002/grl.50560>
- Webster, P. J., Toma, V. E., & Kim, H. M. (2011). Were the 2010 Pakistan floods predictable? *Geophysical Research Letters*, *38*, L04806. <https://doi.org/10.1029/2010GL046346>
- Wernli, H., & Schwierz, C. (2006). Surface cyclones in the ERA-40 dataset (1958–2001). Part I: Novel identification method and global climatology. *Journal of the Atmospheric Sciences*, *63*(10), 2486–2507. <https://doi.org/10.1175/JAS3766.1>
- Wolf, G., Brayshaw, D. J., Klingaman, N. P., & Czaja, A. (2018). Quasi-stationary waves and their impact on European weather and extreme events. *Quarterly Journal of the Royal Meteorological Society*, *144*(717), 2431–2448. <https://doi.org/10.1002/qj.3310>
- Wolter, K., Hoerling, M., Eischeid, J. K., Van Oldenborgh, G. J., Quan, X. W., Walsh, J. E., et al. (2015). How unusual was the cold winter of 2013/14 in the upper midwest? *Bulletin of the American Meteorological Society*, *96*(12), S10–S14. <https://doi.org/10.1175/BAMS-D-15-00126.1>
- Xu, P., Wang, L., Liu, Y., Chen, W., & Huang, P. (2020). The record-breaking heat wave of June 2019 in Central Europe. *Atmospheric Science Letters*, *21*(4), 1–7. <https://doi.org/10.1002/asl.964>
- Zhang, Z. (2016). Parametric regression model for survival data: Weibull regression model as an example. *Annals of Translational Medicine*, *4*(24), 1–8. <https://doi.org/10.21037/atm.2016.08.45>
- Zschenderlein, P., Pfahl, S., Wernli, H., & Fink, A. H. (2020). A Lagrangian analysis of upper-tropospheric anticyclones associated with heat waves in Europe. *Weather Climate Dynamics*, *1*, 191–206. <https://doi.org/10.5194/wcd-1-191-2020>