Atmospheric Research 294 (2023) 106959

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Combinations of drivers that most favor the occurrence of daily precipitation extremes

Luis Gimeno-Sotelo [a,*], Emanuele Bevacqua [b], Luis Gimeno [a]

[a] Centro de Investigación Mariña, Universidade de Vigo, Environmental Physics Laboratory (EPhysLab), Campus da Auga, 32004 Ourense, Spain
[b] Department of Computational Hydrosystems, Helmholtz Centre for Environmental Research, 04318 Leipzig, Germany

ARTICLE INFO

Keywords:
Extreme precipitation
Precipitable water
Moisture transport
Atmospheric instability

ABSTRACT

Previous studies indicate atmospheric instability, total column water vapor, and horizontal moisture transport as major drivers of precipitation extremes, however little is known about how the combination of these drivers affects precipitation extremes across the world. Here, using daily data from the ERA-5 reanalysis spanning the period 1981–2020, we identified the combinations of extreme values for these three major drivers that enhance the probability of daily precipitation extremes on a global scale. Our findings show that extreme daily precipitation is practically impossible without any of these drivers being extreme. Atmospheric instability is the primary driver of precipitation extremes, meaning that, among the three cases of the drivers being extreme in isolation, extreme atmospheric instability is associated with the highest average probability of extreme precipitation over landmasses (29% during December–February, 32% during June–August). When considering the combination of two drivers being simultaneously extreme, joint extremes of atmospheric instability and total column water vapor (and non-extreme horizontal moisture transport) lead to the highest probability of extreme precipitation (69% during December–February, 70% during June–August), which is similar to the probability under three drivers in extreme conditions (67% and 72%). Our results point to a latitudinal variation of the combination that leads to the highest probability of extreme precipitation. In subtropics, the case of the three extreme drivers dominates, whereas in extratropical regions, the dominant combination is that of the joint extremes of atmospheric instability and total column water vapor (and non-extreme horizontal moisture transport). By providing information on the most important drivers of precipitation extremes worldwide, these results can serve as a basis for evaluating precipitation extremes in climate models and understanding projected changes, which is vital for developing robust risk assessments.

1. Introduction

An unequivocal consequence of global warming is the change in precipitation extremes (Douville et al., 2021; Seneviratne et al., 2021; Caretta et al., 2022). With considerable spatial variability, these changes have already been documented for the current climate (e.g. Donat et al., 2016 or Sun et al., 2021) and are projected for future climates (e.g. Westra et al., 2014 or Bao et al., 2017). Behind these changes, there is a thermodynamical cause affecting precipitation extremes everywhere in the world: the increase of extreme precipitation with the increase of the water-holding capacity of the air, which grows at a rate of 6–7% per degree of warming according to the Clausius–Clapeyron relationship (Soden and Held, 2006; Allen and Ingram, 2002). Additionally, there is a dynamic cause: changes in atmospheric circulation and, therefore, in the convergence of atmospheric moisture, which modulate regional extreme precipitation (O'Gorman, 2015; Bao et al., 2017). Depending on the region, such a dynamic effect can enhance or dampen the thermodynamically-driven increase (Pfahl et al., 2017). Thermodynamical and dynamic contributions to changes in extreme precipitation can be well represented with the drivers studied in this article, i.e., atmospheric instability, mostly accounting for dynamic contribution; total column water vapor, mostly accounting for thermodynamical contribution; and horizontal moisture transport, accounting for both dynamic and thermodynamical contributions.

Although the relationship between extreme precipitation and moisture is complex (Neelin et al., 2022), in the first approximation, extreme precipitation broadly scales with moisture content and any indicator of atmospheric instability, such as *vertical velocity*. Unlike total

---

* Corresponding author.
E-mail address: luis.gimeno-sotelo@uvigo.es (L. Gimeno-Sotelo).

https://doi.org/10.1016/j.atmosres.2023.106959
Received 11 April 2023; Received in revised form 17 June 2023; Accepted 5 August 2023

precipitation (e.g., annual or seasonal precipitation), daily extreme precipitation is more sensitive to moisture content than to atmospheric instability (Emori and Brown, 2005; Nie et al., 2018). The exceedance of an atmospheric instability threshold is required for extreme precipitation to occur; however, once this threshold is reached, extreme precipitation increases with increasing water vapor content (Emori and Brown, 2005; Kunkel et al., 2020a). To study precipitation extremes, moisture content can be quantified from the *vertically-integrated water vapor or precipitable water (IWV)*, a variable of great climatic interest as a promising covariate for projecting extreme precipitation in future climates. In a recent study, Kim et al. (2022) pointed out three advantages of considering total water vapor content: its dependence on temperature in general, its estimation from satellites and models, good agreement with radiosonde observations as opposed to precipitation, and its higher correlation with precipitation compared to other covariates, such as surface air temperature or dew point temperature (Roderick et al., 2020).

The relationship between total precipitation and the IWV is often approximated as linear based on simple considerations of the mass balance equation (Hagos et al., 2021; Hagos et al., 2021; Kim et al., 2022), however this relationship is not linear and may vary in different locations and seasons. Some regional studies have shown strong positive correlations between extreme precipitation and IWV, for example for Australia (Roderick et al., 2019) and the contiguous United States (Kunkel et al., 2020b). However, this strong correlation does not seem sufficient to justify the change in extreme precipitation, as shown for extremes in Australia by Bao et al. (2017). Likewise, the linear relationship has also been questioned, for instance Kunkel et al. (2020a) showed that under very high amounts of water vapor, as occurs in regions closer to the tropics or in hot seasons, the increase in daily extreme precipitation is disproportionately larger than the increase in IWV. Such non-linearities highlight the relevance of accounting for changes in dynamical processes when studying precipitation extreme changes. Accordingly, in a recent global study, Kim et al. (2022) found within the tropics a very strong relationship between daily extreme precipitation and IWV only outside of the rainforests; in the extratropical regions (regions outside 30° latitudes, except the interior of North America and North Asia) the relationship is very weak. Overall, they concluded that the IWV is a good driver of daily extreme precipitation in the tropics and is better in hot than cold seasons but not for extratropical regions, where it is necessary to consider other factors such as horizontal moisture transport, which were not considered in their study.

One major reason for the weak influence of the IWV on extreme precipitation in some regions and seasons is the fact that it is not possible to determine how much water vapor is involved in precipitation simply from the amount of water vapor in a column of air at any given time. In fact, the water vapor in the column changes continuously, hence the convergence of water vapor into the column from the surrounding area needs to be considered. Accordingly, the highest amount of moisture measured in the air column at a given time is always much less than the amount of precipitation during actual extreme precipitation events (Trenberth et al., 2003). This indicates that, depending on the time scale used to define the IWV, a constant supply of humidity from the outside, i.e. high *horizontal moisture transport*, is required to maintain high moisture in the atmospheric column. Therefore, on a daily scale, that is when – on average – the amount of extreme precipitation is twice the amount of water vapor (Kunkel et al., 2020a), horizontal moisture transport must be considered as a scaling variable to explain extreme precipitation.

In extratropical regions, it is extremely difficult to generate intense precipitation with only the humidity contained in the atmospheric column. For the occurrence of precipitation extremes, large and sustained contributions of water vapor are required from regions outside the air column (Trenberth et al., 2003; Gimeno et al., 2010), which are often very remote regions (Insua-Costa et al., 2022). Horizontal moisture transport is not spatially or temporally homogeneous, but there are some major horizontal moisture transport mechanisms, namely atmospheric rivers (ARs), low-level jets (LLJs), and tropical cyclones (TCs) (Gimeno et al., 2016) that make the relationship between horizontal moisture transport and extreme precipitation spatially and temporally diverse. There are many ways to quantify horizontal moisture transport (see Gimeno et al., 2012 for a review), most of which are based on *vertically-integrated horizontal moisture transport (IVT)*. IVT is widely used, for example for the identification and characterization of ARs, which are phenomena closely associated with extreme precipitation in extratropical regions (Zhu and Newell, 1998; Gimeno et al., 2014; Payne et al., 2020; Gimeno-Sotelo and Gimeno, 2022). In a recent global study of the relationship between IVT and extreme precipitation on a daily scale using extreme value analysis, Gimeno-Sotelo and Gimeno (2023) showed that the dependence between IVT and extreme precipitation is very weak or negligible in tropical regions, but important in extratropical regions, especially in those where the main mechanisms of horizontal moisture transport are effective, which encompasses some of the areas with the greatest productive economy and population on the planet.

Overall, in the first approximation, daily extreme precipitation may have a very diverse spatial and seasonal dependence on three drivers: atmospheric instability, the water vapor column, and horizontal moisture transport. This study examines how the combination of these three drivers affects extreme precipitation on a global scale. Identifying the combination of drivers that favor extreme precipitation in each region and season will serve both for the design of process-oriented diagnostics (POD) related to extreme precipitation for the evaluation of climate models and as a basis to determine the predominant role of thermodynamical or dynamic factors in changes in extreme precipitation.

2. Data and methods

We used the ERA-5 reanalysis (Hersbach et al., 2020) for the period 1981–2020 to obtain daily data for the following variables at a 0.5° resolution: precipitation, vertically-integrated horizontal moisture transport (IVT), vertically-integrated water vapor (IWV), and vertical velocity at 500 hPa. IWV (also known as precipitable water or total column water vapor) and vertical velocity at 500 hPa were directly obtained from the reanalysis, whereas IVT was computed as the vertical integral of eastward and northward water vapor flux (IVT_u and IVT_v, respectively). The IWV and IVT can be expressed as follows:

$$IWV = \frac{1}{g}\int_{\Omega} q\, dp,$$

$$IVT = \sqrt{\left(\frac{1}{g}\int_{\Omega} q\, u\, dp\right)^2 + \left(\frac{1}{g}\int_{\Omega} q\, v\, dp\right)^2} = \sqrt{IVT_u{}^2 + IVT_v{}^2},$$

where q refers to specific humidity, u to zonal wind, v to meridional wind, g to gravitational acceleration, and Ω to the entire atmospheric column. Please note that in this article vertical velocity refers to "$-\omega$", where $\omega = \frac{dp}{dt}$, and p refers to the atmospheric pressure, i.e., "$-\omega$" is the measure that is used for representing atmospheric instability (Holton, 1973).

In this study, using ERA-5 reanalysis data allows for analyzing the relationship between extreme precipitation and the extremes of the three studied drivers (i.e., IWV, IVT and vertical velocity) on a global scale. The limitations of using reanalysis data for these variables have been comprehensively discussed in previous studies (Gimeno-Sotelo et al., 2022, Gimeno-Sotelo and Gimeno, 2023). As explained in Gimeno-Sotelo and Gimeno, 2023, we use ERA-5 data only for the period 1981–2020 because the recently released backward extension up to 1950 does not provide reliable IVT data.

To study the effect of seasonality on the obtained results, the analysis was performed independently for the boreal and austral winters, i.e. December–February (DJF) and June–August (JJA), respectively. For each of the analyzed seasons, we define an extreme value of a variable when the variable is larger than its corresponding 95th percentile (computed for the corresponding season within the period 1981–2020), and vice-versa for non-extreme values. We also tested that using different thresholds (90th and 98th percentile) does not substantially affect the results. Successively, based on empirical counting, we estimate the conditional probability of extreme precipitation for all combinations of extreme and non-extreme conditions of the drivers. Specifically, we consider the following combinations of drivers:

i) the three drivers being non-extreme, which is the reference case here.
ii) one driver being extreme and the other two drivers being non-extreme.
iii) two drivers being extreme and the other driver being non-extreme.
iv) the three drivers being extreme.

The conditional probability of extreme precipitation for a given combination of drivers in extreme conditions is estimated as the ratio between the number of days in which both extreme precipitation (Pcp_{ext}) and the combination of drivers occurred, and the total number of days in which the combination occurred, that is:

$$\widehat{P}(Pcp_{ext}|combination\ of\ extreme\ drivers) = \frac{\#\{Pcp_{ext}, combination\ of\ extreme\ drivers\}}{\#\{combination\ of\ extreme\ drivers\}},$$

where “#” refers to the number of elements of a set.

Among the combinations considered (those with only one extreme driver, those with two extreme drivers, or all the combinations), the dominant combination is the one that maximises the conditional probability of extreme precipitation.

To quantify the influence of extreme conditions of the drivers on precipitation extremes, we compute the difference between the probability associated with the cases (ii-iv) and the probability associated with the reference case under no extreme drivers (i). Statistical significance for these differences is assessed using a test based on continuity-corrected score intervals (see Method 11 in Newcombe, 1998), using R software (R Core Team, 2022), namely the function *prop.test()*; see Supplementary Method for further details.

3. Results and discussion

We begin by analyzing the estimated probability of occurrence of extreme daily precipitation when none of the three drivers (IWV, IVT, and vertical velocity) is extreme. In line with the physically-based choice of the precipitation drivers, probabilities are very low, in particular, they are smaller than or equal to 5% (the value expected under the independence of precipitation extreme occurrence from the drivers) over virtually all (>99.9%) landmasses in DJF and JJA. This result indicates that at least one of the three drivers must be extreme for daily precipitation extremes to occur. In the following subsections, we analyze the extent to which precipitation extremes occurs when one, two, or all three drivers are extreme.

3.1. Only one extreme driver

Fig. 1 shows which is the *dominant driver* of precipitation extremes over different regions, i.e. which among the three drivers being extreme in isolation maximise the probability of precipitation extremes. In general, vertical velocity is the most frequent dominant driver. IWV dominates in tropical and subtropical regions, with the exception of the central axis of the ITCZ, while IVT dominates in the regions where atmospheric rivers occur (Gimeno et al., 2016). Specifically, extreme vertical velocity dominates over 59% of global landmasses in DJF (65% in JJA), while IWV dominates over only 26% of landmasses in DJF (27% in JJA) and extreme IVT over 15% of landmasses in DJF (8% in JJA).

Fig. 2 shows the differences between the estimated probability of extreme daily precipitation when only one of the three drivers is extreme and the probability in the reference case of no extreme drivers. The absolute values of the conditional probabilities related to the three conditions in Fig. 2 are shown in Fig. S1.

In line with Fig. 1, Fig. 2 shows that the highest deviations from the reference case are found when vertical velocity is extreme, and the other two drivers are not. That is, vertical velocity is the main driver of precipitation extremes, especially over landmasses, where precipitation extremes are most impactful. Probabilities differ significantly from the reference case in most regions worldwide (Fig. 2a,b), except for the subtropical oceanic areas and some continental areas where extreme instability by itself does not guarantee the occurrence of extreme precipitation. Low probabilities are found in subtropical oceanic subsidence regions (Fig. S1a,b), which are areas with very low precipitation, with the greatest effect in the corresponding summer. In the rest of the oceanic areas, high probabilities (40%–60%) are generally observed with even higher values (60%–80%) in some areas of the Intertropical Convergence Zone (ITCZ). Over landmasses, the pattern is heterogeneous, including regions with high probabilities (40%–60%), such as the continental areas of the ITCZ, the Amazon and Congo basins, the east of the North American and Asian continents, and the interior of the European continent in summer.

Regarding the case of only extreme IVT (Fig. 2c,d) and only extreme IWV (Fig. 2e,f), the probability of precipitation extremes is also significantly different from that in the reference case in many regions. In the case of only extreme IVT, probabilities in the order of 40%–60% are found in winter in some regions affected by atmospheric rivers, such as the west coast of North America, Norway, and the east coast of Russia (Fig. S1c). Specifically, these high values mark very well atmospheric rivers' oceanic track and landfalling areas (Fig. 2c,d). The strong relationship between IVT and extreme precipitation and its link with the occurrence of atmospheric rivers has already been revealed in recent studies by Gimeno-Sotelo and Gimeno (2022, 2023). In the case of only extreme IWV, we found probabilities of 40%–60% in the entire tropical and subtropical regions (with values reaching 60%–80% locally), except for the ITCZ axis, where it is low (Fig. S1e,f). This result agrees with the recent work by Kim et al. (2022), indicating that IWV is necessary for extreme precipitation to occur in tropical regions; in extratropical regions, extreme IWV in isolation does not guarantee extreme precipitation, as additional drivers are required.

3.2. Two extreme drivers

Despite the dominant contribution of vertical velocity to precipitation extremes (Fig. 1), all drivers contribute to a certain extent to extreme precipitation (Fig. 2). Hence, the combination of two drivers in extreme conditions may enhance the occurrence of precipitation extremes. As shown in Fig. 3, the dominant combination of two drivers is extreme vertical velocity and IWV (and non-extreme IVT). Such a combination dominates over 76% of global landmasses in DJF and 78% in JJA. However, in some areas of maximum occurrence of atmospheric rivers, such as the coastal areas of western North America and Europe, the combination of extreme vertical velocity and IVT (and non-extreme IWV) dominates – this combination dominates over 17% and 16% of global landmasses in DJF and JJA, respectively.

We find that the probability of extreme daily precipitation increases greatly when two of the three drivers involved are extreme and the other is not (Figs. 4 and S2). Notably, the values of the difference of probabilities with respect to the reference case are typically higher than those associated with only one driver in extreme conditions (compare Fig. 2 with Fig. 4).

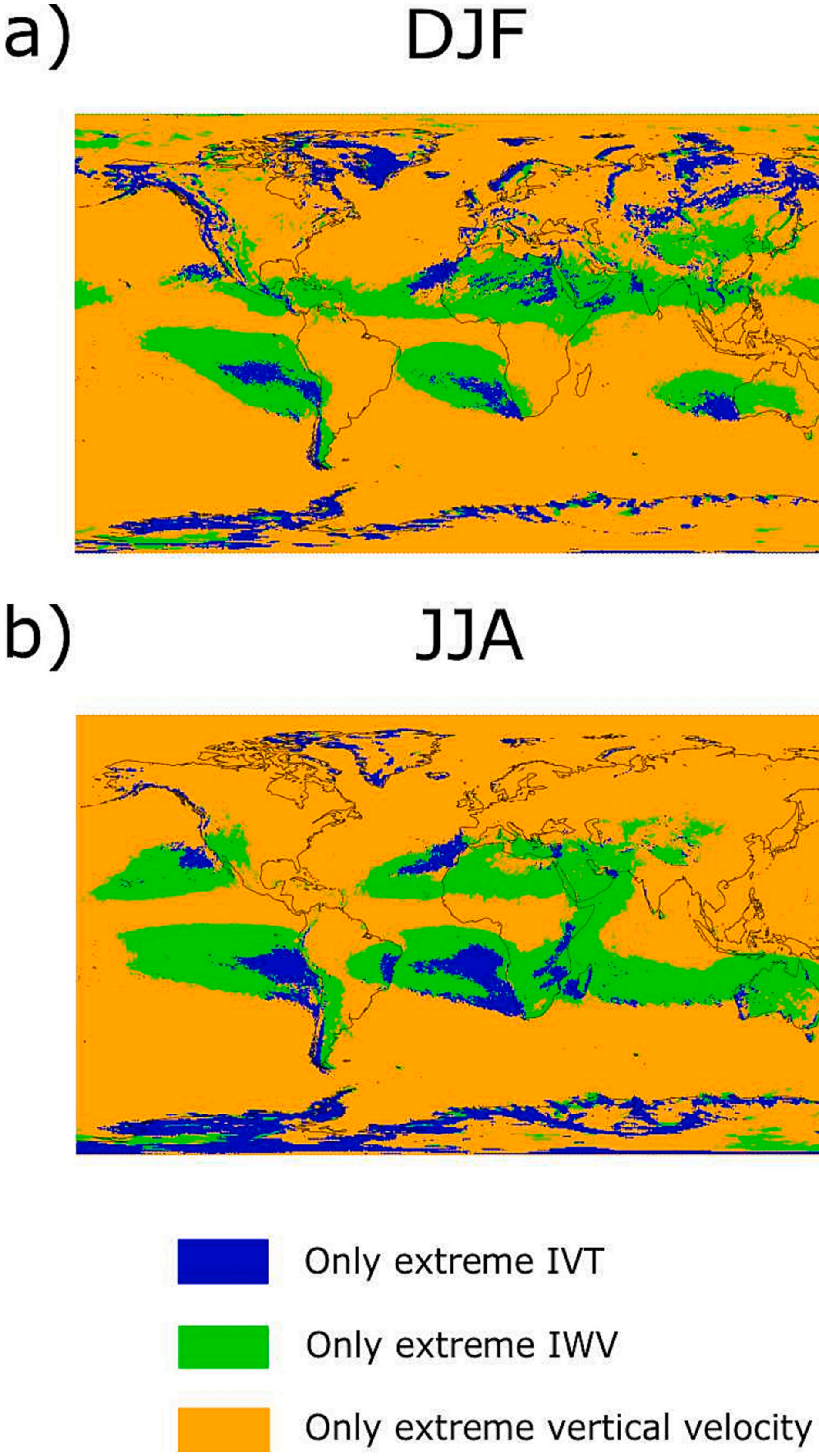

Fig. 1. Spatial pattern of the dominant driver of precipitation extremes, that is the combination of one extreme driver in isolation with the highest associated extreme precipitation probability, for a) December–February and b) June–August.

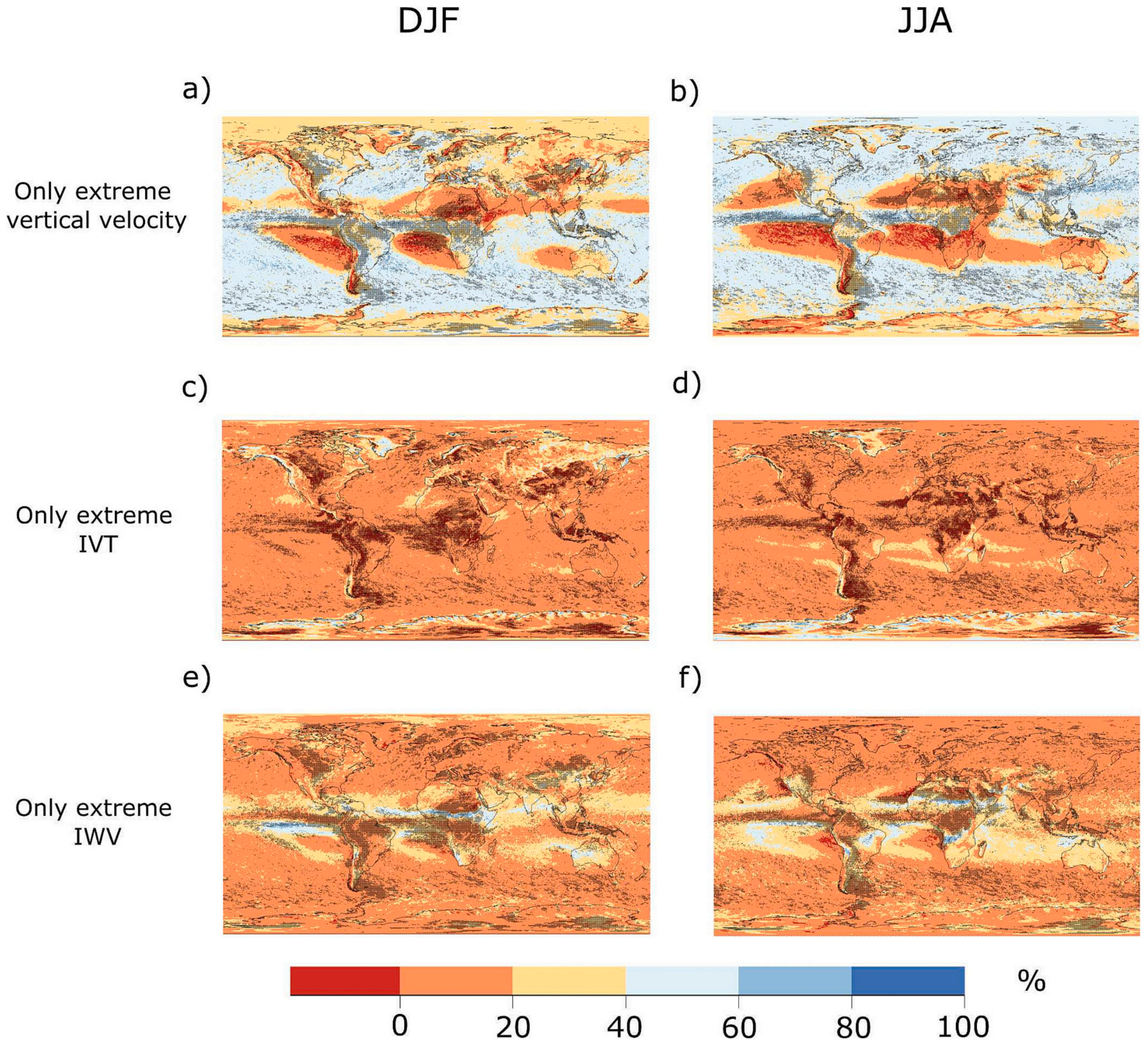

Fig. 2. Difference between the conditional probabilities of extreme precipitation for the combinations of one extreme driver in isolation and the conditional probability in the reference case, i.e. when the three drivers are not extreme. Grid points without stippling are those whose values are significantly different from 0 at 95% confidence level. a), b) Refer to the combination of only extreme vertical velocity; c), d) only extreme IVT; and e), f) only extreme IWV, for December–February and June–August, respectively.

The combination of extreme vertical velocity and IVT, under non-extreme IWV (Fig. 4a,b) leads to more areas of non-significant differences with respect to the reference case compared to the combination of extreme vertical velocity and IWV (Fig. 4c,d). These non-significant differences for the combination of extreme vertical velocity and IVT are especially remarkable over inner continental areas. Globally, the combination of extreme vertical velocity and IVT is associated with a lower probability of precipitation extremes (60–80%; see Fig. S2a,b) than the case of extreme vertical velocity and IWV (80%–100%; see Fig. S2c,d), which is the combination of two extreme drivers that leads to the highest probabilities of precipitation extremes. Accordingly, areas of low probability are also more extended in the former than in the latter situation.

In the extratropics, combined vertical velocity and IVT extremes increase the probability of precipitation extremes substantially (compared to individual extreme drivers in isolation). This indicates that atmospheric dynamics play a very important role in the genesis of precipitation extremes in the extratropics through large-scale weather systems, such as extratropical cyclones or fronts; however, they are only really relevant when there is sufficient moisture advection (IVT) to guarantee high values of moisture in the column (Gimeno et al., 2010; Kunkel et al., 2012).

Regarding the combined extremes of vertical velocity and IWV, under non-extreme IVT, probabilities are significantly different from the reference case in most regions, with the exceptions of the areas affected by subtropical anticyclones and coastal regions with high orography, e.g. north-western North America, south-western South America, and Norway (Fig. 4c,d).

The situation for the other combination of drivers, i.e. extreme IVT and IWV (and non-extreme vertical velocity), is different (Fig. 4e,f, and Fig. S2e,f). Probabilities are generally lower than in the case of the other combinations of two drivers (with most regions with values below 40%). The highest probabilities are found in the subtropics (with values between 60% and 80% in many of these areas). Subtropics are the greatest moisture sources of the planet (Gimeno et al., 2012), climatologically characterized by the strongest evaporation minus precipitation areas over the world, i.e., the highest climatological values of divergence of moisture fluxes. The situation of extremely high IVT and IWV in those regions implies the reverse of the climatological conditions, that is, the convergence of moisture fluxes. As moisture is maximum at low levels, convergence of moisture fluxes implies convergence of winds at low levels which is associated strongly in subtropical regions with atmospheric instability and consequently extreme precipitation (Mo et al., 2021). This is revealed under non-extreme vertical velocity (being high but not necessarily extreme), with probabilities of extreme precipitation being reasonably high, and is much more evident under extreme vertical

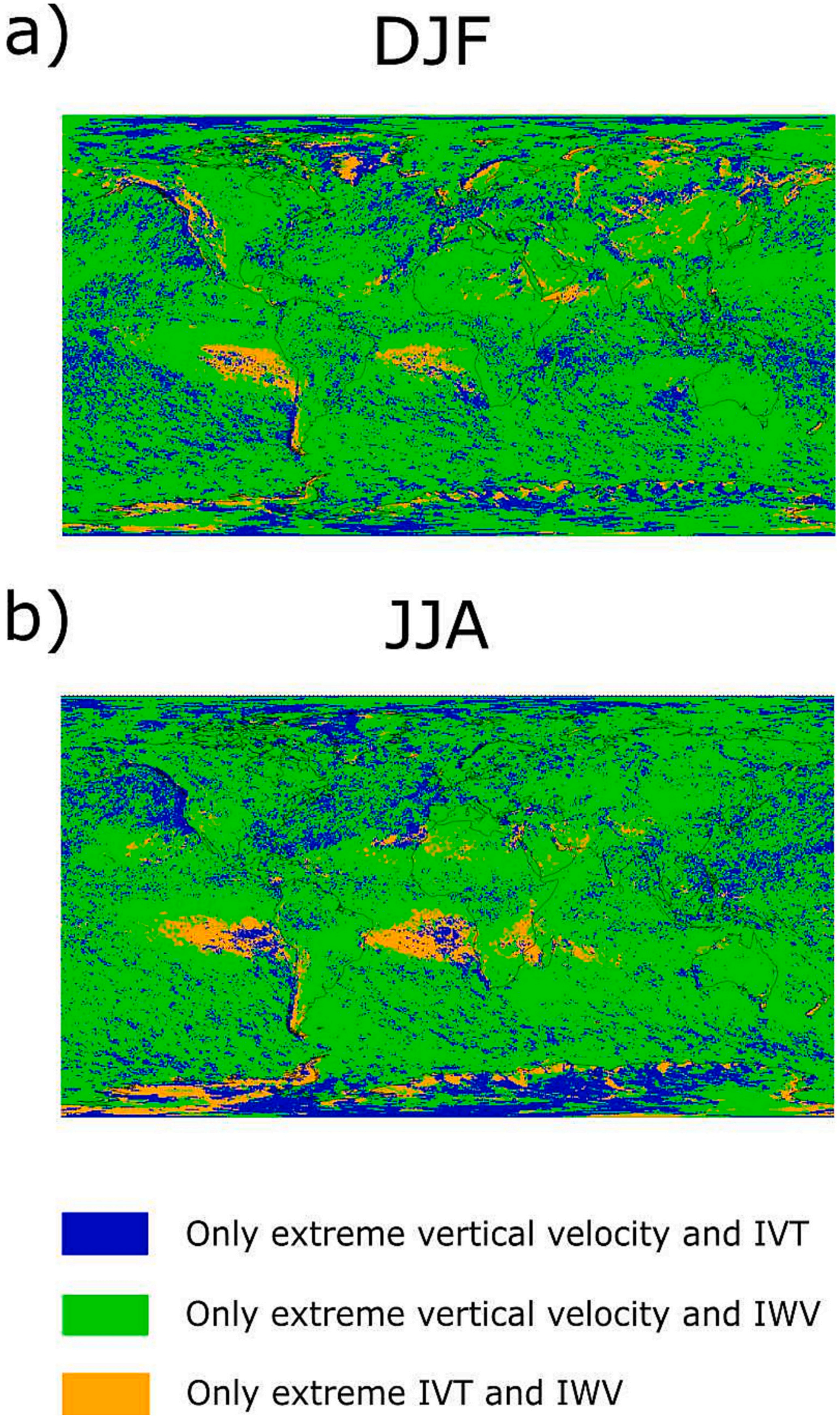

Fig. 3. Spatial pattern of the combination of two extreme drivers associated with the highest extreme precipitation probability for each grid point, for a) December–February and b) June–August.

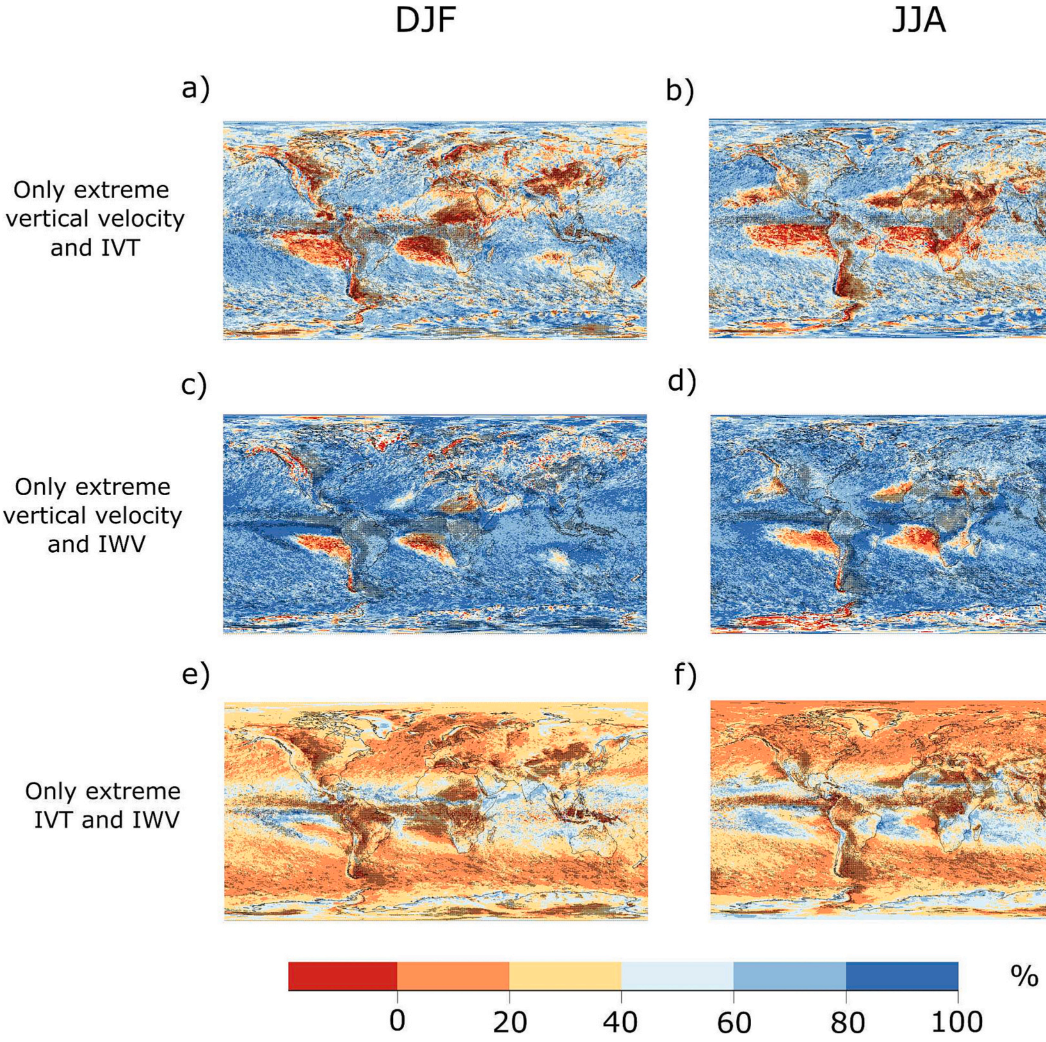

Fig. 4. Difference between the conditional probabilities of extreme precipitation for the combinations of two extreme drivers and the conditional probability in the reference case, i.e. when the three drivers are not extreme. Grid points without stippling are those whose values are significantly different from 0 at 95% confidence level. a), b) Refer to the combination of only extreme vertical velocity and IVT; c), d) only extreme vertical velocity and IWV; and e), f) only extreme IVT and IWV, for December–February and June–August, respectively.

velocity (see Subsection 3.3), with probability values between 80% and 100% in those regions.

3.3. *Three extreme drivers*

When the three drivers, that is, vertical velocity, IWV, and IVT, are simultaneously extreme (Figs. 5 and S3), probabilities of occurrence of extreme daily precipitation are generally between 80% and 100%. Probabilities are not statistically different from the case of no extremes only over the subtropical anticyclonic areas (areas with very low precipitation) and some regions in north-western North America, south-western South America, Scandinavia, the Mediterranean and continental areas of Eurasia.

3.4. *The most relevant combination of drivers*

We inspect which is the combination among all of those investigated so far that maximises the probability of precipitation extremes. Fig. 6 shows the dominant combination and how it varies as a function of latitude over landmasses. Two dominant combinations exist: (1) extreme vertical velocity and IWV (under non-extreme IVT) and (2) the three extreme drivers. Both combinations dominate over about 45% of landmasses, both in DJF and JJA. In general, the combination of the three drivers dominates in the subtropics and the combination of vertical velocity and IWV dominates elsewhere (Fig. 6b,d). This is in line with the fact that adding extreme IVT to the combination of extreme vertical velocity and IWV results in higher values of both IWV and vertical velocity in subtropics, thus increasing the chances of precipitation extremes, but not in a large part of extratropics (mainly the regions of inner American and Asian continental areas) (Fig. S4). This is in agreement with what was explained in Subsection 3.2: in the subtropics, extreme atmospheric instability is associated with low-level winds convergence, which added to extreme IVT implies an enhancement of the moisture flux convergence. Consequently, in the subtropics, under extreme IVT there is an increase in IWV and even in atmospheric instability by the thermodynamics/dynamics interplay (a higher low-level moisture is associated with higher thermodynamical instability and higher vertical velocity) (Kunkel et al., 2020a). Therefore, the combination of the three extreme drivers maximises the probability of extreme precipitation in subtropics. Regarding the regions where the combination of vertical velocity and IWV dominates (e.g. inner continental areas), they coincide with areas where it is not necessary to have extreme values of advected moisture (extreme values of IVT) for extreme precipitation to take place, as moisture comes from the soil by terrestrial sources (Gimeno et al., 2020), mainly from evapotranspiration (Miralles et al., 2016). Furthermore, in these extratropical regions atmospheric

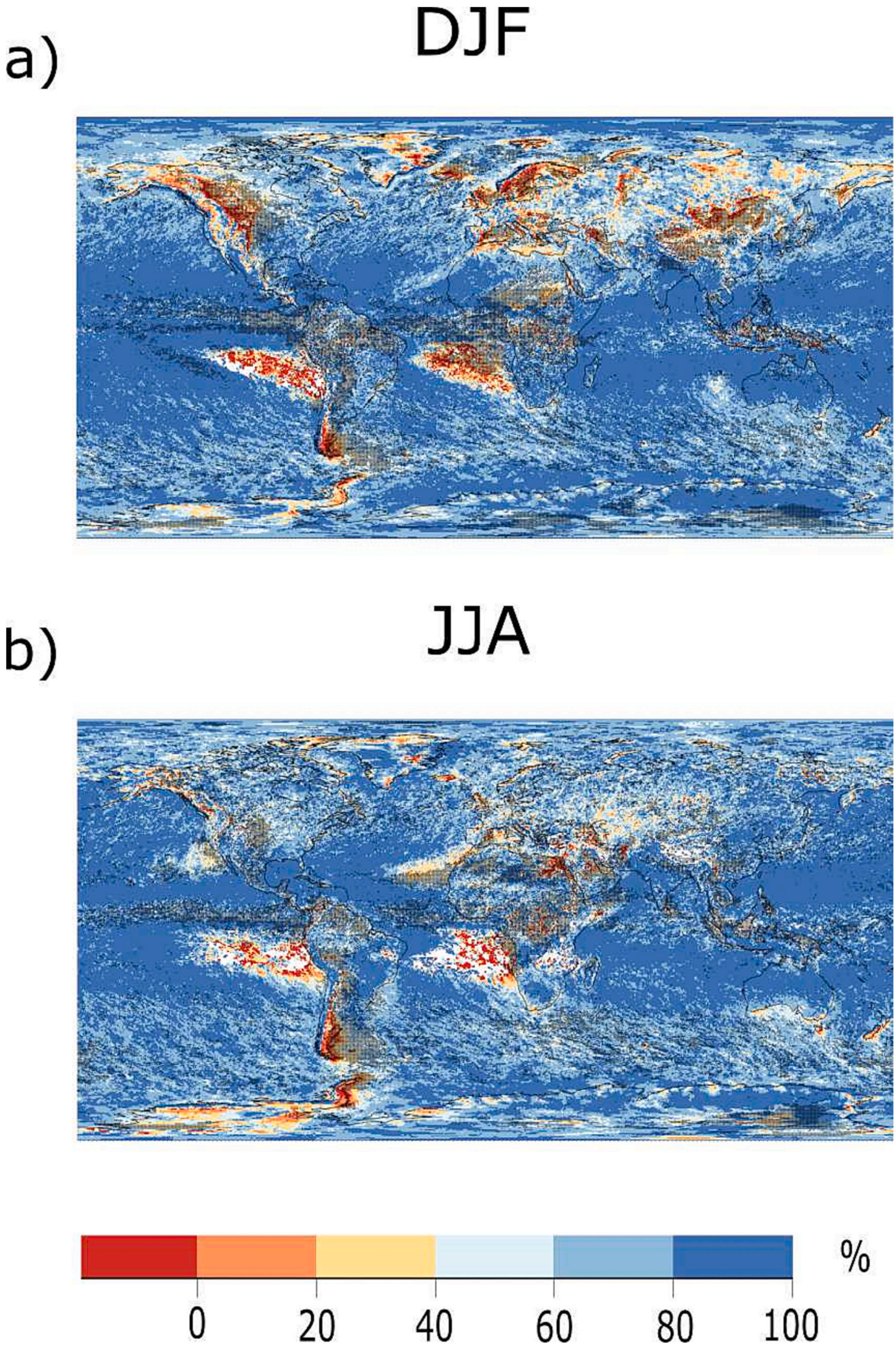

Fig. 5. Difference between the conditional probability of extreme precipitation for the case of the three extreme drivers and the conditional probability in the reference case, i.e. when the three drivers are not extreme, for a) December–February and b) June–August. Grid points without stippling are those whose values are significantly different from 0 at 95% confidence level.

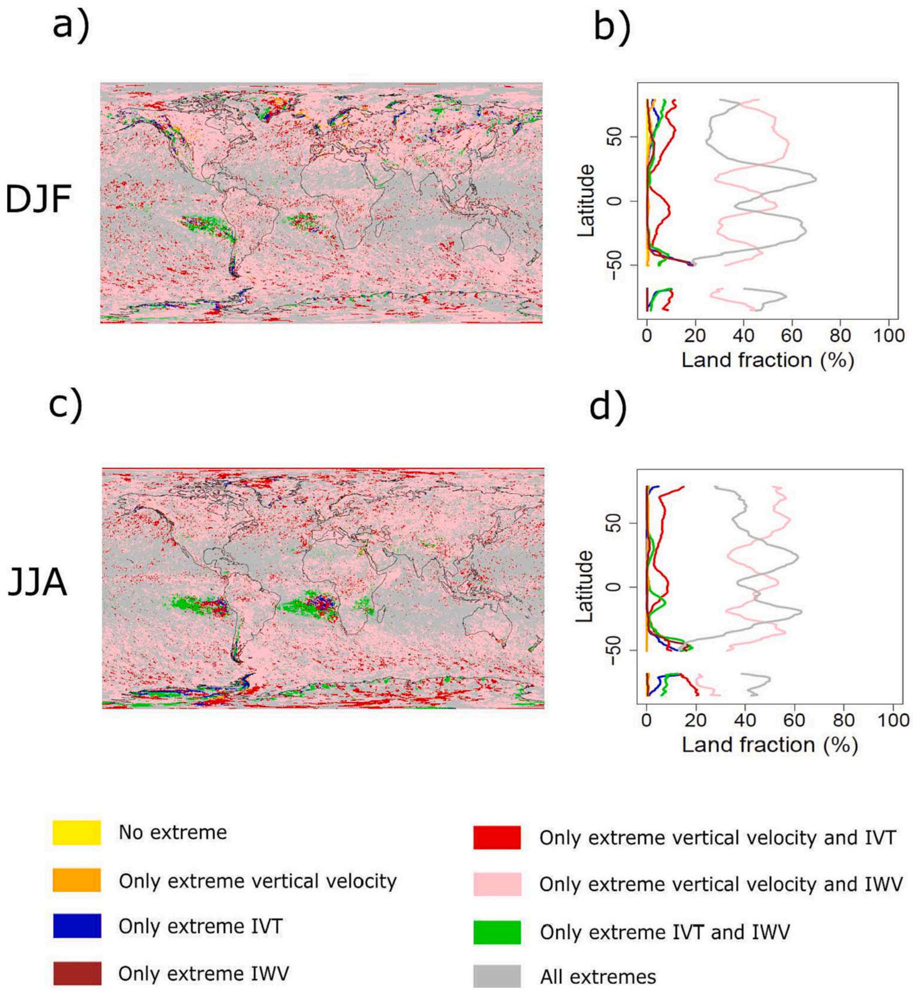

Fig. 6. a) Spatial pattern of the combination of drivers (with either one, two or three drivers in extreme conditions) associated with the highest extreme precipitation probability and b) associated latitudinal variation of the land fraction dominated by each of the combinations, for December–February. c-d) As a-b), but for June–August.

instability is dominated by baroclinic instability in which the link atmospheric instability-convergence of low-level winds is not so strong as for low latitudes, and the thermodynamics/dynamics interplay (stronger moisture-stronger atmospheric instability) is minimized because of the low moisture values. As such, there are many American and Eurasian continental regions where the combination of extreme vertical velocity and IWV (under non-extreme IVT) results in a higher probability of extreme precipitation than the combination of the three extreme drivers (Fig. 6a,c), as being evident in the values of fraction of landmasses dominated by that two-driver combination in extratropical regions of the Northern Hemisphere (Fig. 6b,d). The influence of atmospheric rivers on extreme precipitation is also observable in the predominant combination of extreme vertical velocity and IVT (and non-extreme IWV) in some coastal regions in Europe and North America in DJF, and in the dominance of the combination of the three drivers in Antarctica.

The average extreme precipitation probability under each of the conditions considered in this study is shown in Fig. S5, for the globe and for land and oceanic areas separately. Regarding landmasses, the combination of extreme vertical velocity and IWV (under non-extreme IVT) and that of the three extreme drivers are those that lead to the highest values (69% in DJF and 70% in JJA for the two-driver combination, and 67% in DJF and 72% in JJA for the three-driver one). This result highlights that focusing only on extreme vertical velocity and IWV is at least as adequate as considering the three extreme drivers (or even better in the case of DJF) when studying the drivers of extreme precipitation over land areas. The third combination in importance is the one of extreme vertical velocity and IVT (under non-extreme IWV), producing values that are substantially lower than in the previous two cases (42% of average probability over landmasses in DJF and 44% in JJA). Regarding the combinations of only one extreme driver, the case of only extreme vertical velocity clearly outperforms the other two cases, reaching an average probability of 29% over landmasses in DJF and 32% in JJA.

A further analysis was performed at the regional level, focusing on the IPCC land subregions (Fig. S6). For each subregion, we identified the dominant (second-dominant) combination as the one with the highest (second-highest) regionally averaged conditional probability of extreme precipitation (Figs. 7 and S7). The resulting dominant and second-dominant combinations are everywhere either the combination of extreme vertical velocity and IWV (under non-extreme IVT) or that of the three extreme drivers. We find that the spatial pattern of the dominant combination is the same in DJF and JJA and, in line with Fig. 6, the combination of extreme vertical velocity and IWV (under non-extreme IVT) is dominant in most extratropical regions. The three-driver combination is dominant in all the IPCC subregions included in the monsoon precipitation domain (Wang and Ding, 2008), which extends the traditional monsoon domain from Asian-Australian-west African monsoon to the North and South American monsoons and the southern African monsoon and that is related to the concept of global monsoon (Wang et al., 2023). Moreover, the three-driver combination also

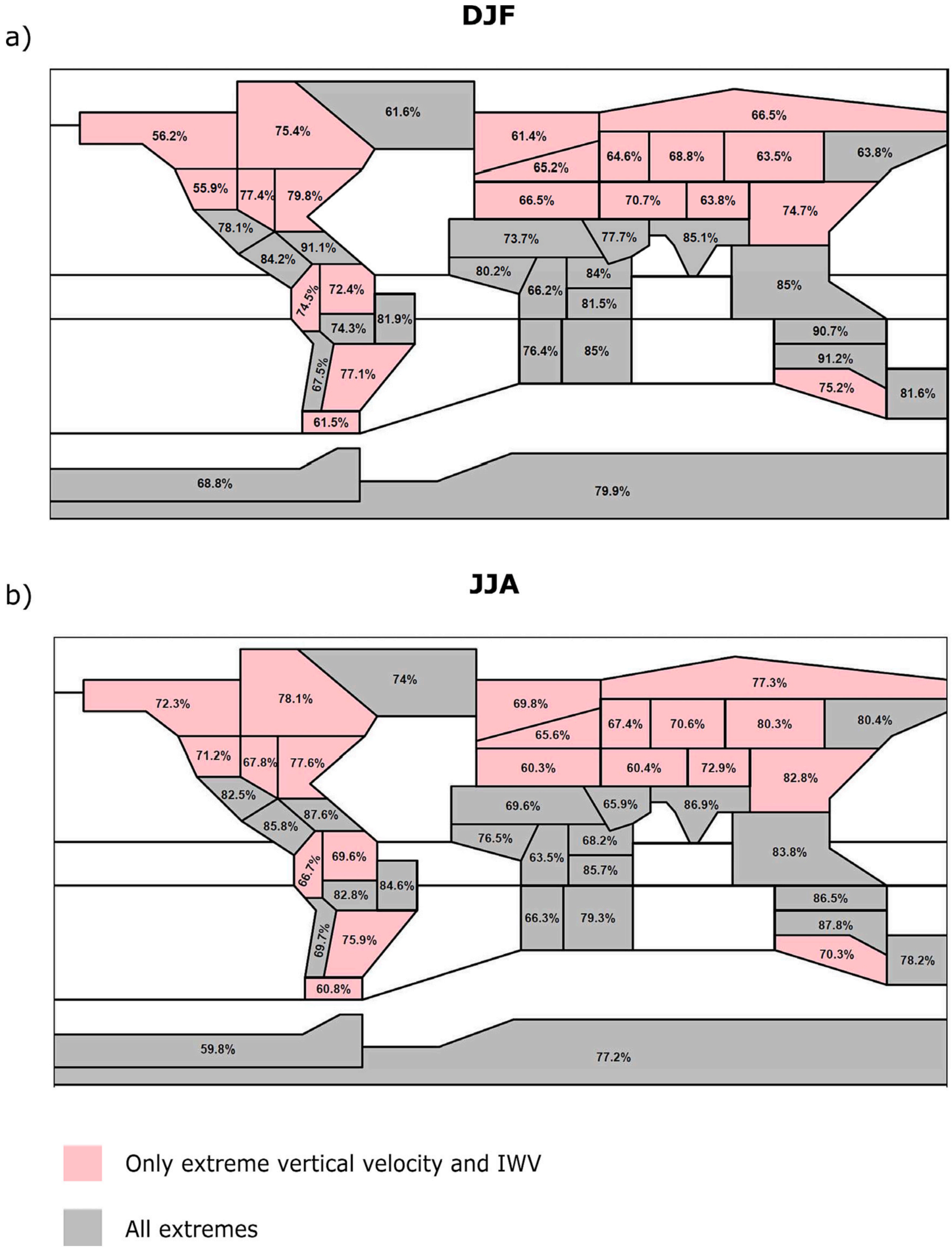

Fig. 7. Spatial pattern of the combination of drivers (with either one, two or three drivers in extreme conditions) associated with the highest average probability of extreme precipitation for each of the IPCC subregions used in this study, for a) December–February and b) June–August. For each subregion, the value of the average probability (in percentage) can be found inside its corresponding polygon.

dominates in polar regions, where extreme values of advected moisture (extreme values of IVT) are necessary for extreme precipitation to take place, as the moisture content in the air column is low because of the low temperatures. This analysis based on IPCC regions was also performed using other thresholds to define the extreme values (90th percentile and 98th percentile) and also considering two subperiods separately (1981–2000 and 2001–2020), obtaining the same spatial pattern for the dominant combination to that presented here.

4. Conclusions

In this study, the combinations of extremes of vertical velocity, total column water vapor, and horizontal moisture transport that most favor the occurrence of extreme daily precipitation on a global scale were studied. This study has some limitations associated with the quality of precipitation and water vapor column data from the reanalysis and the metric used to estimate atmospheric instability. Reanalyses are products built from a data assimilation scheme and global circulation models that ingest all available observations; however, despite the fact that ERA-5 is one of the most modern and best quality products, the quality of the precipitation data is generally low for regions with sparse observations, small-scale convective processes, and very complex orography. In this study atmospheric instability has been estimated as "-ω" at 500 hPa from the ERA5 reanalysis. This metric captures movements very well at a synoptic scale (100 to 1000 km), which includes precipitating systems linked to baroclinic instability (e.g. extratropical cyclones, fronts), but does not do so well for systems that occur on the mesoscale (10 to 100 km), in which thermodynamical instability (e.g. storms) is very relevant. For both reasons, the results of this study have greater confidence in the extratropical regions than in the tropical and main tropical rainforest regions.

These are the main conclusions of this study:

- If none of these drivers is extreme, there is virtually no chance of extreme daily precipitation. Hence, extreme values of at least one of them are required for extreme daily precipitation.
- Vertical velocity extremes alone have a greater influence on extreme daily precipitation, being associated with an average probability of 29% over landmasses in December–February and 32% in June–August. However, there are some exceptions, such as the subtropics or the regions with strong atmospheric river activity, where extreme total column water vapor alone or extreme horizontal moisture transport alone, respectively, is more advantageous for precipitation extremes.
- The combination of two extreme drivers that most influences extreme daily precipitation is that of extreme vertical velocity and total column water vapor (and non-extreme horizontal moisture transport). It leads to probabilities of extreme daily precipitation which are comparable to or even higher than those associated with the three drivers in extreme conditions (69% of average probability over landmasses in December–February and 70% in June–August for that two-driver combination; and 67% in December–February and 72% in June–August for the three-driver one). Focusing on continental regions, the combination of extreme vertical velocity and total column water vapor (and non-extreme horizontal moisture transport) is dominant in most extratropical areas, whereas that of extreme values of the three drivers is dominant in those regions included in the monsoon precipitation domain as well as in polar areas.

This study has implications for the design of process-oriented diagnostics (POD) for evaluating climate models. When designing a POD for extreme daily precipitation, it was found that the most convenient drivers to consider were vertical velocity and total column water vapor, except for some regions with high horizontal moisture transport activity. The use of only two drivers, one representing dynamic factors (vertical velocity) and the other thermodynamical factors (total column water vapor) could be useful to study the relative importance of these two factors in the current and projected extreme precipitation.

Author contributions

Luis Gimeno-Sotelo performed the analysis and generated the figures. All the authors contributed to the conceptualization, interpretation, discussions, writing and reviewing of the manuscript.

CRediT authorship contribution statement

Luis Gimeno-Sotelo: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Emanuele Bevacqua:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Luis Gimeno:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

ERA5 reanalysis data are publicly available and can be obtained from https://cds.climate.copernicus.eu.

Acknowledgments

Luis Gimeno-Sotelo and Luis Gimeno acknowledge support from the SETESTRELO project (grant no. PID2021-122314OB-I00) funded by the Ministerio de Ciencia e Innovación, Spain. The EPhysLab group was co-funded by Xunta de Galicia, Consellería de Cultura, Educación e Universidade, under project ED431C 2021/44 "Programa de Consolidación e Estructuración de Unidades de Investigación Competitivas". Luis Gimeno-Sotelo was supported by a UVigo PhD grant ("Axudas para contratos predoutorais da Universidade de Vigo"). Emanuele Bevacqua has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003469. Luis Gimeno-Sotelo and Emanuele Bevacqua acknowledge the European COST Action DAMOCLES (CA17109). In addition, this work has been possible thanks to the computing resources and technical support provided by CESGA (Centro de Supercomputación de Galicia). Funding for open access charge: Universidade de Vigo/CISUG

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosres.2023.106959.

References

Allen, M.R., Ingram, W.J., 2002. Constraints on future changes in climate and the hydrologic cycle. Nature 419 (6903), 228–232. https://doi.org/10.1038/nature01092.

Bao, J., Sherwood, S.C., Alexander, L.V., Evans, J.P., 2017. Future increases in extreme precipitation exceed observed scaling rates. Nat. Clim. Chang. 7 (2), 128–132. https://doi.org/10.1038/nclimate3201.

Caretta, M.A., et al., 2022. Water. In: Pörtner, H.O., et al. (Eds.), Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.

Donat, M.G., Lowry, A.L., Alexander, L.V., O'Gorman, P.A., Maher, N., 2016. More extreme precipitation in the world's dry and wet regions. Nat. Clim. Chang. 6 (5), 508–513. https://doi.org/10.1038/nclimate2941.

Douville, H., et al., 2021. Water Cycle Changes. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., Et al.]. Cambridge University Press. In Press.

Emori, S., Brown, S.J., 2005. Dynamic and thermodynamic changes in mean and extreme precipitation under changed climate. Geophys. Res. Lett. 32 https://doi.org/10.1029/2005GL023272. L17706.

Gimeno, L., Nieto, R., Trigo, R.M., Vicente-Serrano, S.M., López-Moreno, J.I., 2010. Where does the Iberian Peninsula Moisture come from? An answer based on a Lagrangian approach. J. Hydrometeorol. 11 (2), 421–436. https://doi.org/10.1175/2009JHM1182.1.

Gimeno, L., Stohl, A., Trigo, R.M., Dominguez, F., Yoshimura, K., Yu, L., Drumond, A., Durán-Quesada, A.M., Nieto, R., 2012. Oceanic and terrestrial sources of continental precipitation. Rev. Geophys. 50 (4).

Gimeno, L., Nieto, R., Vázquez, M., Lavers, D.A., 2014. Atmospheric rivers: a mini-review. Front. Earth Sci. 2, 2. https://doi.org/10.3389/feart.2014.00002.

Gimeno, L., Dominguez, F., Nieto, R., Trigo, R., Drumond, A., Reason, C.J., Taschetto, A. S., Ramos, A.M., Kumar, R., Marengo, J., 2016. Major mechanisms of atmospheric moisture transport and their role in extreme precipitation events. Annu. Rev. Environ. Resour. 41, 117–141.

Gimeno, L., Nieto, R., Sorí, R., 2020. The growing importance of oceanic moisture sources for continental precipitation. Npj climate and Atmospheric. Science 3 (1), 27.

Gimeno-Sotelo, L., Gimeno, L., 2022. Concurrent extreme events of atmospheric moisture transport and continental precipitation: the role of landfalling atmospheric rivers. Atmos. Res. 278, 106356 https://doi.org/10.1016/j.atmosres.2022.106356.

Gimeno-Sotelo, L., Gimeno, L., 2023. Where does the link between atmospheric moisture transport and extreme precipitation matter? Weather Clim. Extremes 39, 100536.

Gimeno-Sotelo, L., de Zea Bermudez, P., Algarra, I., Gimeno, L., 2022. Modelling hydrometeorological extremes associated to the moisture transport driven by the Great Plains low-level jet. Stoch. Env. Res. Risk A. 1–25.

Hagos, S.M., Leung, L.R., Garuba, O.A., Demott, C., Harrop, B., Lu, J., Ahn, M., 2021. The Relationship between Precipitation and Precipitable Water in CMIP6 Simulations and Implications for Tropical Climatology and Change. J. Clim. 34 (5), 1587–1600. https://doi.org/10.1175/JCLI-D-20-0211.1.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Thépaut, J.N., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146 (730), 1999–2049.

Holton, J.R., 1973. An introduction to dynamic meteorology. Am. J. Phys. 41 (5), 752–754.

Insua-Costa, D., Senande-Rivera, M., Llasat, M.C., Miguez-Macho, G., 2022. A global perspective on western Mediterranean precipitation extremes. npj Clim. Atmos. Sci. 5, 1, 1–7. https://doi.org/10.1038/s41612-022-00234-w.

Kim, S., Sharma, A., Wasko, C., Nathan, R., 2022. Linking total precipitable water to precipitation extremes globally. Earth's. Future 10. https://doi.org/10.1029/2021EF002473 e2021EF002473.

Kunkel, K.E., Easterling, D.R., Kristovich, D.A.R., Gleason, B., Stoecker, L., Smith, R., 2012. Meteorological causes of the secular variations in observed extreme precipitation events for the conterminous United States. J. Hydrometeorol. 13 (3), 1131–1141. http://www.jstor.org/stable/24914694.

Kunkel, K.E., Stevens, S.E., Stevens, L.E., Karl, T.R., 2020a. Observed climatological relationships of extreme daily precipitation events with precipitable water and vertical velocity in the contiguous United States. Geophys. Res. Lett. 47 https://doi.org/10.1029/2019GL086721 e2019GL086721.

Kunkel, K.E., Karl, T.R., Squires, M.F., Yin, X., Stegall, S.T., Easterling, D.R., 2020b. Precipitation Extremes: Trends and Relationships with Average Precipitation and Precipitable Water in the Contiguous United States. J. Appl. Meteorol. Climatol. 59 (1), 125–142. https://doi.org/10.1175/JAMC-D-19-0185.1.

Miralles, D.G., Nieto, R., McDowell, N.G., Dorigo, W.A., Verhoest, N.E., Liu, Y.Y., Teuling, A.J., Dolman, A.J., Good, S.P., Gimeno, L., 2016. Contribution of water-limited ecoregions to their own supply of rainfall. Environ. Res. Lett. 11 (12), 124007.

Mo, R., So, R., Brugman, M.M., Mooney, C., Liu, A.Q., Jakob, M., Castellan, A., Vingarzan, R., 2021. Column relative humidity and primary condensation rate as two useful supplements to atmospheric river analysis. Water Resour. Res. 57 (11) e2021WR029678.

Neelin, J.D., Martinez-Villalobos, C., Stechmann, S.N., Ahmed, F., Chen, G., Norris, J.M., Kuo, Y.H., Lenderink, G., 2022. Precipitation Extremes and Water Vapor. Curr. Clim. Chang. Rep. 1 (8), 17–33, 2022 8.

Newcombe, R.G., 1998. Interval estimation for the difference between independent proportions: comparison of eleven methods. Stat. Med. 17 (8), 873–890.

Nie, J., Sobel, A.H., Shaevitz, D.A., Wang, S., 2018. Dynamic amplification of extreme precipitation sensitivity. Proc. Natl. Acad. Sci. 115, 9467–9472.

O'Gorman, P.A., 2015. Precipitation extremes under climate change. Curr. Clim. Change Rep. 1 (2), 49–59. https://doi.org/10.1007/s40641-015-0009-3.

Payne, A.E., Demory, M.E., Leung, L.R., Ramos, A.M., Shields, C.A., Rutz, J.J., Ralph, F. M., 2020. Responses and impacts of atmospheric rivers to climate change. Nat. Rev. Earth Environ. 1 (3), 143–157.

Pfahl, S., O'Gorman, P., Fischer, E., 2017. Understanding the regional pattern of projected future changes in extreme precipitation. Nat. Clim. Chang. 7, 423–427. https://doi.org/10.1038/nclimate3287.

R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Roderick, T.P., Wasko, C., Sharma, A., 2019. Atmospheric moisture measurements explain increases in tropical rainfall extremes. Geophys. Res. Lett. 46, 1375–1382. https://doi.org/10.1029/2018GL080833.

Roderick, T.P., Wasko, C., Sharma, A., 2020. An improved covariate for projecting future rainfall extremes. Water Resour. Res. 56 https://doi.org/10.1029/2019WR026924 e2019WR026924.

Seneviratne, S.I., et al., 2021. Weather and climate Extreme events in a changing climate. In: Masson-Delmotte, V., et al. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press (In Press).

Soden, B.J., Held, I.M., 2006. An assessment of climate feedbacks in coupled ocean-atmosphere models. J. Clim. 19 (23) https://doi.org/10.1175/JCLI9028.1, 6263–3360.

Sun, Q., Zhang, X., Zwiers, F., Westra, S., Alexander, L.V., 2021. A global, continental, and regional analysis of changes in extreme precipitation. J. Clim. 34 (1), 243–258. https://doi.org/10.1175/jcli-d-19-0892.1.

Trenberth, K.E., Dai, A., Rasmussen, R.M., Parsons, D.B., 2003. The changing character of precipitation. Bull. Am. Meteorol. Soc. 84 (9), 1205–1218.

Wang, B., Ding, Q., 2008. Global monsoon: Dominant mode of annual variation in the tropics. Dyn. Atmos. Oceans 44 (3–4), 165–183.

Wang, B., Jin, C., Liu, J., 2023. Global monsoon: Concept and dynamic response to anthropogenic warming. MAUSAM 74 (2), 493–502.

Westra, S., Fowler, H.J., Evans, J.P., Alexander, L.V., Berg, P., Johnson, F., et al., 2014. Future changes to the intensity and frequency of short-duration extreme rainfall. Rev. Geophys. 52, 522–555. https://doi.org/10.1002/2014RG000464.

Zhu, Y., Newell, R.E., 1998. A proposed algorithm for moisture fluxes from atmospheric rivers. Mon. Weather Rev. 126 (3), 725–735.