Final author comments for wcd-2020-28
Extreme wet seasons – their definition and relationship with synoptic scale weather systems
E. Flaounas, M. Röthlisberger, M. Boettcher, M. Sprenger and H. Wernli

We thank both reviewers for their detailed comments, which are very helpful for further improving our manuscript. In particular, several figures have been revised to increase the clarity of the presentation of the results.

Reviewer #1

This thorough paper introduces a novel method to investigate seasonal precipitation extremes and the large-scale and synoptic conditions that give rise to these. This is an important study as such seasonal extremes can be responsible for a number of socioeconomic impacts.

The paper is mostly clear and well-written, with a few places that could use some clarification. I give specific comments below.

We are thankful for the positive and constructive review. We took into account all comments and corrections.

1. Most of the English usage is British English, but there are some examples of “characterize”. Please ensure consistency, as per the WCD instructions.

Done. English style is now consistent throughout the text.

2. Line 68: “signalizes” -> “signals”.

Done.

3. Line 87: The use of the word “provoke” is a little strange – perhaps use “give rise to” or “produce”.

Done.

4. Line 174: I’m not sure what is meant by the “half of the month”. This is not referred to elsewhere – is this a mistake?

Indeed, this is a mistake, "half of the" has been removed to better match the content of the figure.

5. Line 187 and throughout: please use capitals for Northern Hemisphere and Southern Hemisphere.

Done.

6. Throughout: The use of the word “amount” for precipitation, might be better as “volume”.

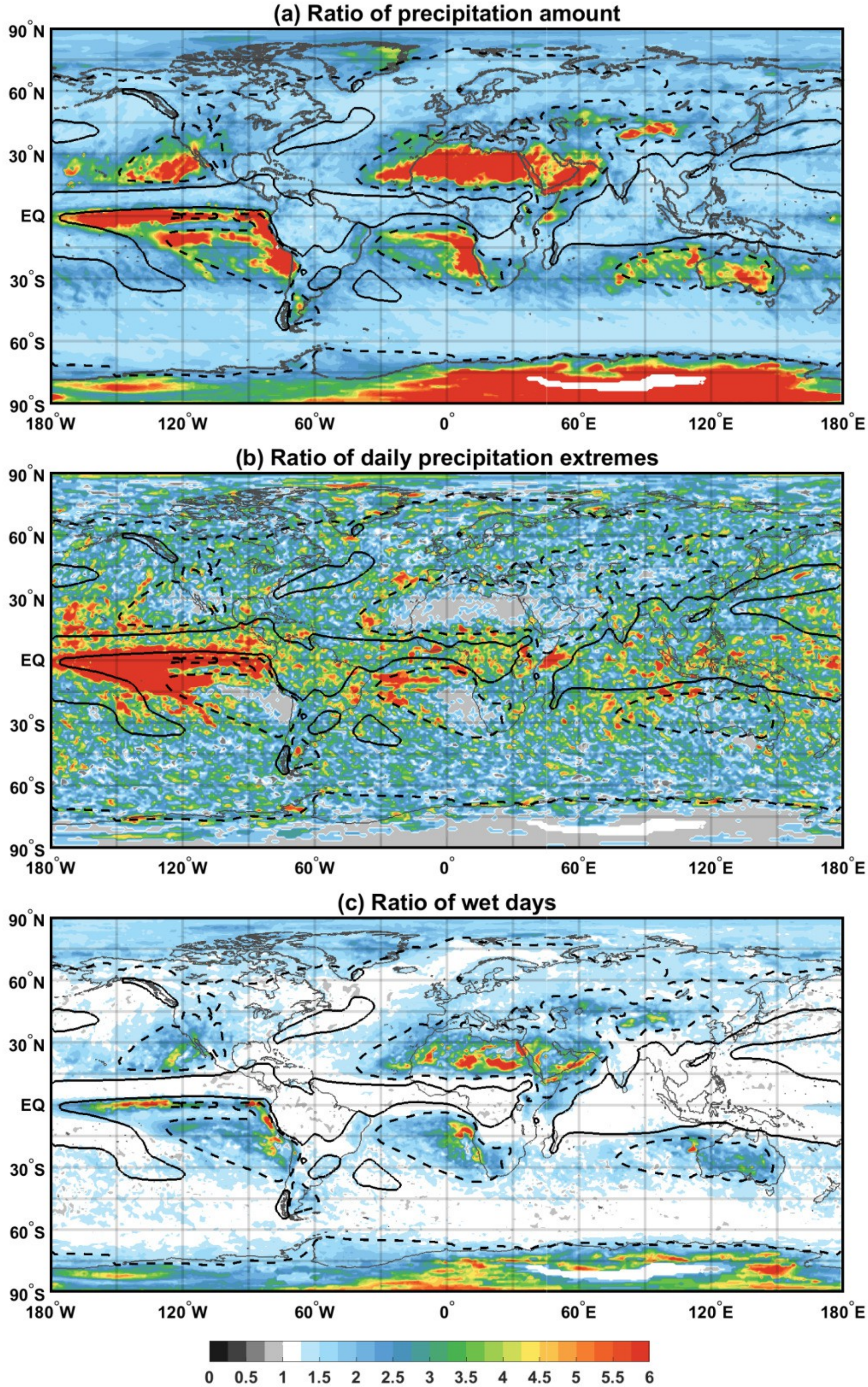
We chose to retain the word "amount" as this term is more commonly found in the scientific literature.

7. Line 219: The language here is a bit unclear – “contrasting precipitation amount ratios”. I’m not sure what this means.

The sentence has been rephrased.

8. Line 220: But it seems that in parts of the ITCZ, there are high ratios of both the extremes and the wet days. One thing that might be useful in this figure (Figure 4) could be to show the climatological precipitation in fine contours (or just a couple of contours), so that the reader doesn't have to check back to the climatology to see how well things match up.

Thank you for the suggestion. Figure 4 now includes two isohyet contours: for 500 and 1500 mm (see new version below). This will help the reader to identify areas of frequent and scarce precipitation. In line 220 we removed the word "only" to avoid absolute statements.



Revised Figure 4 (a) Ratio of precipitation amount of extreme seasons with respect to the seasonal average, and **(b)** the ratio of the number of daily precipitation extremes included in an extreme season with respect to the seasonal average. **(c)** as **(b)** but for the number of wet days. Dashed and solid contours depict annual average precipitation of 500 and 1500 mm.

9. Line 232: It is stated here that most of the ratios exceed 1, but the figures do not show values below 1. If there are values below 1, the contour intervals on the figure should reflect that and allow the reader to see where this occurs.

Thank you for this careful comment. The colorbar of Fig. 4 was changed to include values below 1.

Only 3% of all grid points have a wet day ratio < 1. The majority of these wet day ratios (75%) range between 0.95 and 1, with a median of 0.98.

For daily precipitation extremes, 13% of all grid points have ratios < 1. The majority of these ratios (75%) range between 0.8 and 1 with a median of 0.98.

Ratios < 1 are now mentioned at the end of the paragraph:

"Before further discussing these patterns, it is noteworthy that 13% of all grid points feature ratios of daily precipitation extremes below 1 (Fig. 5a). These values are concentrated in areas of scarce precipitation and are depicted by grey colors in Fig. 4b. For wet days, ratios below 1 are even less common, they occur only for 3% of all grid points and typically exhibit values between 0.9 and 1 (Fig. 5a). In contrast to daily precipitation extremes, these grid points are scattered across areas of frequent precipitation (e.g. ITCZ and storm tracks), where wet day ratios are close to 1, i.e. where extreme seasons occur with roughly the climatological value of wet days."

10. Figure 5: I really like this way of characterising the extreme seasons. However, it is very difficult to tell the difference between the green/cyan colours. As such some of the writing around this figure is difficult to understand.

Colours in the figure have been changed (see new Fig. 5 below) and the five points below (a)-(e) have been adequately addressed as suggested.

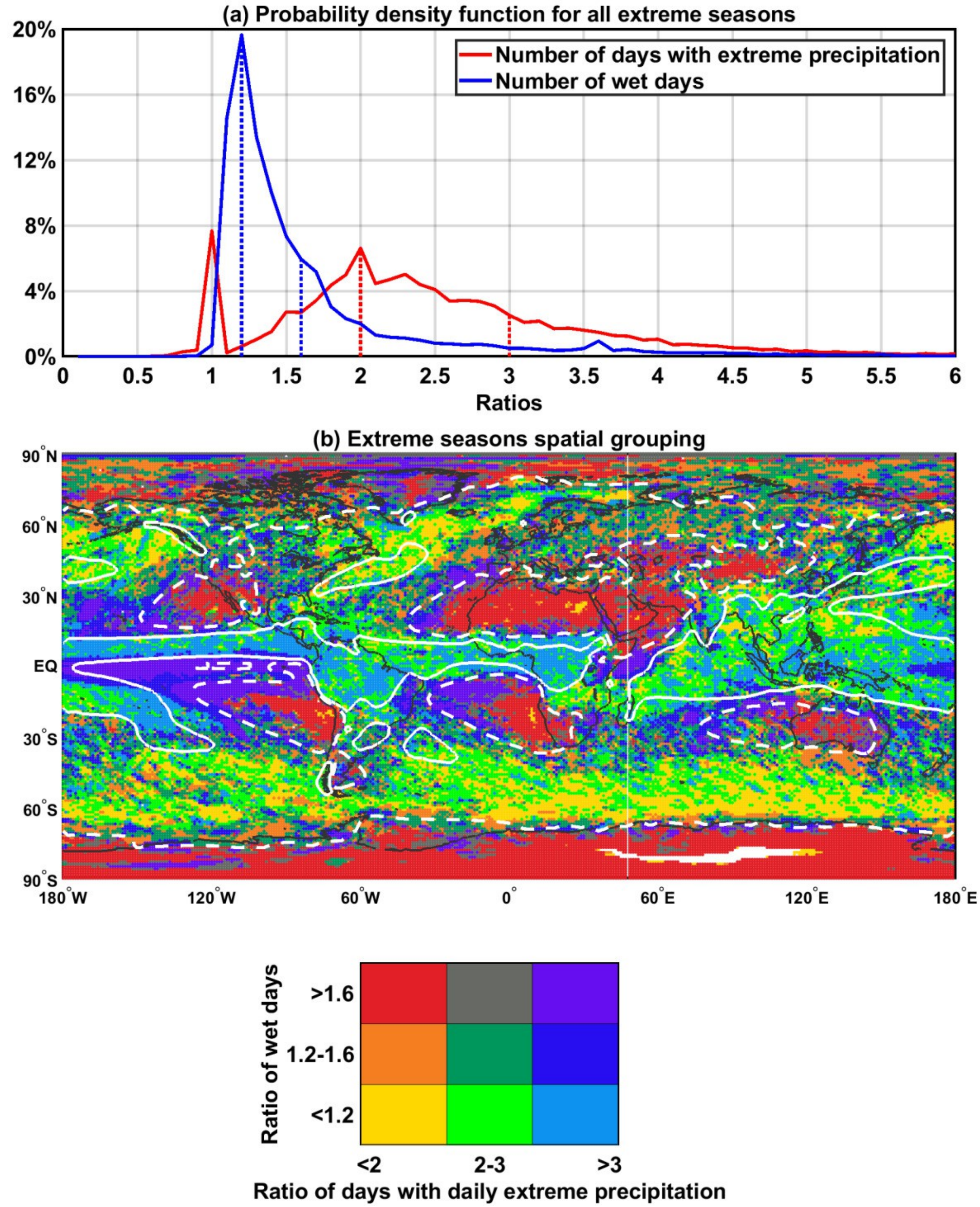
a. E.g. line 243: The cyan colour referred to over equatorial Africa to me looks like the light blue from the bottom right bin. So it would appear to have a high ratio of daily extremes and low ratio of wet days. Especially as "cyan" is referred to again to describe this same colour on line 253.

b. It is mentioned in multiple places about the wet day ratio less than 1.2, but the 9-panel bins show "<2".

c. Line 259: "20 to 60% more wet days". This is confusing as everywhere else the ratios are referred to – please change this to be similar to previous.

d. In this figure it may be useful to also have the climatological precipitation contours.

e. In panel (a) there is typo in "precipitation".



Revised Figure 5 (a) Probability density function of the number of ratios of daily precipitation extremes and wet days for all extreme seasons and for all grid points (ratios with respect to the seasonal average). Vertical dotted lines correspond to ratios of 1.2, 1.6, 2 and 3. **(b)** Attribution of grid points to nine categories of pairs of ratios of the number of wet days and of daily precipitation extremes. Dashed and solid white contours depict annual average precipitation of 500 and 1500 mm, respectively. Dotted lines in **(a)** show the category boundaries used in **(b)**.

11. Line 276: El Nino and La Nina -> El Niño and La Niña.

Done.

12. Section 4.2: I would be interested to know the sensitivity of the results to defining these core periods. The core periods end up being typically longer than the initially 90 days anyway, so what is the impact of not worrying about it? I suppose the main difference will be when looking at the overlap of the patches with the synoptic systems. It does seem that the method ends up becoming rather complex, so it would be good to know if this extra complexity is necessary.

Thank you for this insightful comment. The reviewer quite rightly notices a key advantage of defining these core periods: Considering the full duration of the extreme wet periods would make the matching with weather features somewhat fuzzy, as of course numerous weather features would be matched to an extreme season patch despite not occurring during an extremely wet 90-day period. The definition of a core period helps to ensure that the overwhelming majority of weather features that are matched to the extreme season patches, indeed occur during an extremely wet period at the grid points where they occurred. We agree with the reviewer that the definition of a core period adds indeed to the complexity of our methodology, but it assures that patches are temporally and spatially representative of an extreme season. We added the following remark in section 4.2 (see also next comment):

"*It is noteworthy that core periods may not include days with locally intense precipitation events that don't affect a large fraction of the patch area. The intention of the core period is to consider precipitation in the entire larger-scale area of the extreme season patch, and to identify the time period that is most important for precipitation in the patch as a whole.*"

Given that WCD provides an opportunity for online discussions, we would like to further deepen the discussion on the methods that we use. The complexity of our methodology originates from the fact that we adopt a flexible definition of extreme seasons, i.e. using a flexible 90-day period of maximum accumulation of precipitation. In an alternative methodology, we could identify extreme seasons by predefining this time period. For instance, we could identify extremely wet summers (defined as JJA in the Northern Hemisphere) at every grid point. Then, building the patches would be a straightforward procedure and "free-of-complexity", by simply connecting neighbouring grid points that present extreme summers in the same year. The simplicity of this alternative method is intriguing, but it also comes with shortcomings that we overcome with our approach: first, the patch building and analyses would need to be repeated for each season (e.g. for winters, summers, autumns and springs), whereas with our approach, we can obtain a single global view on very wet 90-day periods. Even more importantly, the precipitation season of a specific region might not always fit with the fixed seasons. For instance, the onset of the African monsoon is in the beginning of July. As a result, an extremely wet monsoon season that has a late onset risks of not being documented as an extremely wet season since most of the precipitation will take place in autumn and not in summer. In summary, our method allows high flexibility in the definition of extreme seasons with the price of increasing the complexity. This is a compromise, but it is also where the novelty and strength of our method lies: it provides a new, flexible definition of seasonal precipitation and proposes an approach to define the spatial extent of a wet season. We hope that future studies will build on this, and these studies might further refine the detailed aspects of the patch building and propose alternative metrics to quantify the characteristics of the identified seasons.

13. In figure 7, because there are fewer grid points contributing, the total precipitation is less, but some of those points may be experiencing their largest precipitation at that time. How is this taken into account?

This comment addresses directly the motivation of this study. Indeed, a day may be excluded by the core period even if a certain grid point is experiencing high precipitation. Also, in connection with our reply to the previous comment, our motivation here is to obtain patches that are representative for the temporal and spatial scales of seasonal precipitation. Applying additional criteria that force core periods to include local intense precipitation events would bias our method towards singular events and would thus eclipse cases where extreme seasonal precipitation is more due to the aggregation of "moderate events".

14. Line 249: Why has this particular case been chosen?

We assume here that the Reviewer refers to line 349. Both cases were chosen for their similarity and for sharing the same characterisation of extreme seasons in Fig. 5. We found that the additional "Portuguese case" would provide some insights into the spatial structures and variability of the patterns that produce extreme seasons in the subtropics/mid-latitudes. Nevertheless, it would be too much to include additional cases in each subsection of section 5. We included the following phrase to justify our choice:

"*Figure 8 provides insight into the complex relationship between precipitation, cyclones and TMEs for this patch, but also for another patch of similar latitudinal extent and orientation that affected the Iberian Peninsula in late autumn 1989 (note that this additional patch is not depicted in Fig. 7).*"

15. Line 387: Please consider rewording this to make it clear it is a ratio.

Done.

16. Case studies: It is a bit confusing that the different cases show different things – it is hard to compare. Why is the Arctic case (Fig. 10) shown as a precipitation anomaly ratio rather than the total precipitation as in the other cases?

Our choice of case studies meant to cover different latitudes, but also to demonstrate the implications of different weather systems. In this regard, the figures in Section 5 are not consistent, i.e., they present different fields. We agree with the reviewer that this can be confusing for the reader. To lighten section 5, we have removed section 5.4 and thus we now present three cases instead of four. In these three cases, we consistently present the relationship between the patches, the four weather systems and precipitation in terms of ratios and climatological anomalies of occurrence (also according to the query of the second Reviewer). This makes the new Figs. 8, 9 and 10 more consistent to each other. Please find the revised Figs. 8-10 towards the end of this document.

17. Line 409: "same dates" and grid points.

Done.

18. Lines 430-432 (first sentence): This information would be better in the introduction or methods.

These sentences have been rephrased.

19. Line 440: Remove "relatively". There are relatively many WCBs even though there are few in absolute terms.

Done.

20. Line 443-444: Again, this information could be relocated.

We agree that these phrases better suit the introduction. However, we prefer to retain these phrases to ease understanding of readers who are not familiar with TMEs to interpret the figures' content.

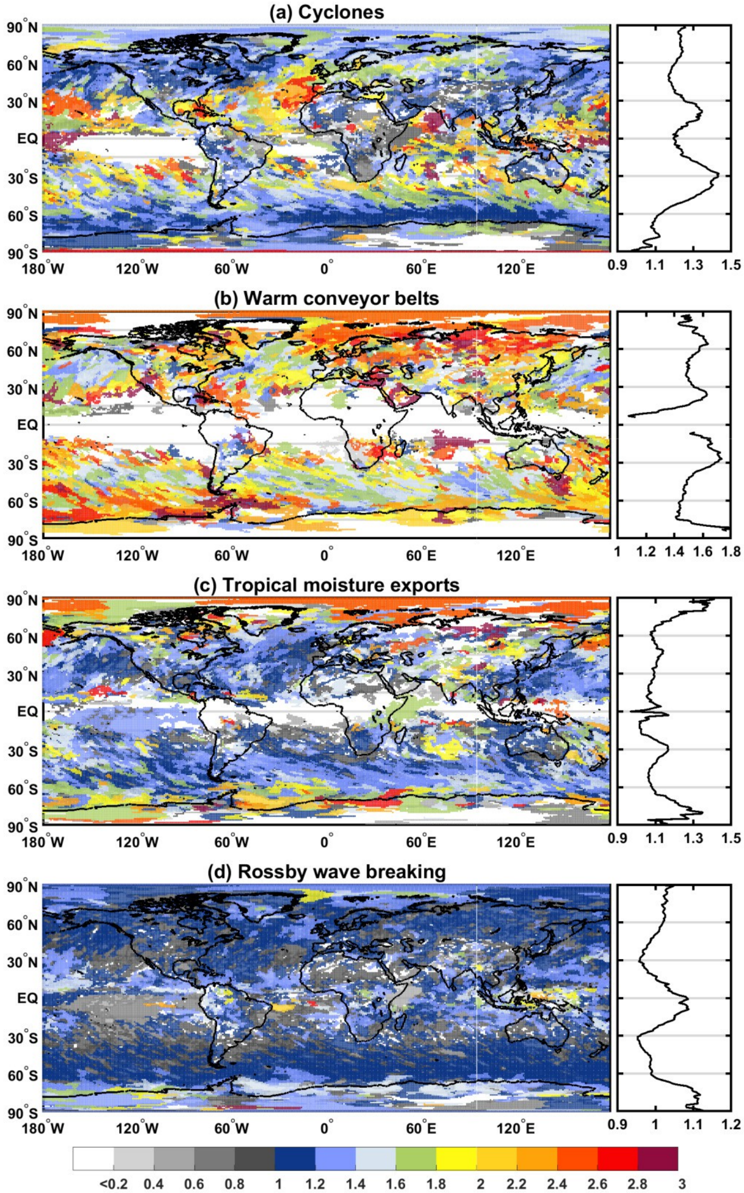
21. Line 449: "less" -> "fewer".

Done.

22. Figure 12: There are places where the ratio is less than 1 (especially for the RWB), but this is not mentioned. Why might you expect fewer than normal of these systems? Could this vary depending on the time of year?

Thank you for this insightful comment. There are indeed several patches where the ratio of the weather features is below 1. First, we changed the colorbar to ease contrast between patches with ratios below and above 1 (see revised Fig. 12 below). In addition, we added the following discussion at the end of Section 6:

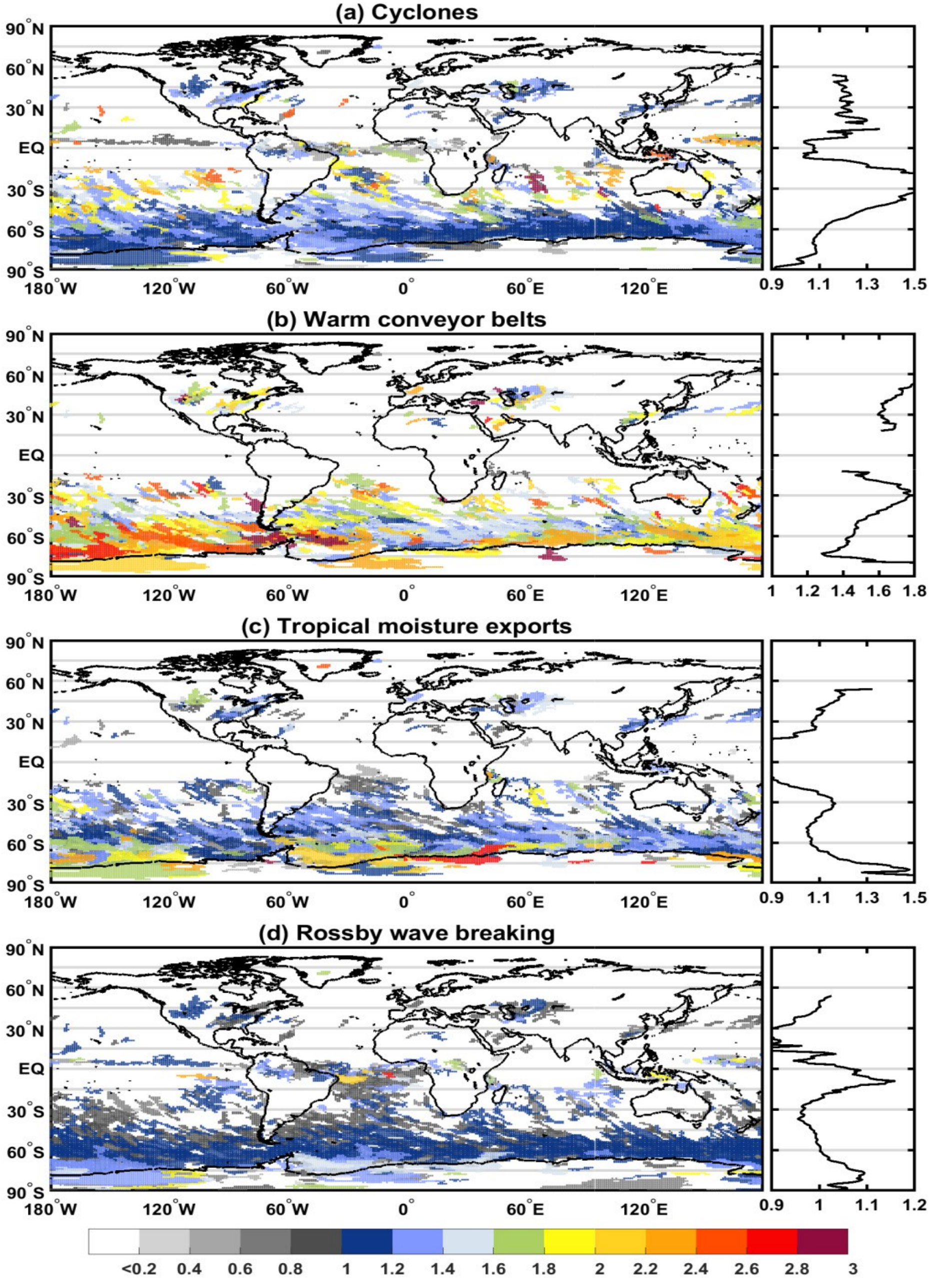
"*It is noteworthy that in all panels of Fig. 11 there are several patches where the ratios are below 1. This indicates that in the core periods of these patches fewer weather systems occurred than in the climatology. This can plausibly occur if the considered system is not decisive for extreme seasonal precipitation. In such a case, the frequency of occurrence in extreme seasons might be close to the climatological average, i.e. the ratio varies randomly around 1. For instance, the patch covering large part of the great Australian Bight, at the central-south side of Australia, has a ratio below 1 for TMEs (Fig. 11c) whereas cyclones and WCBs have relatively high ratios of 1.6 and 2.2. It is plausible that TMEs do not play a crucial role to the formation of this extreme season compared to other more important contributions from cyclones and WCBs. It is finally noteworthy that we adopted a phenomenological approach to assess the contribution of specific weather systems to the extreme seasons, which only considers the occurrence of a weather system (categorical yes or no) but not specifically its associated precipitation. As a result, it cannot be excluded that a specific weather system might strongly contribute to the formation of an extreme season, even if its seasonal occurrence frequency is lower than in the climatology.*"



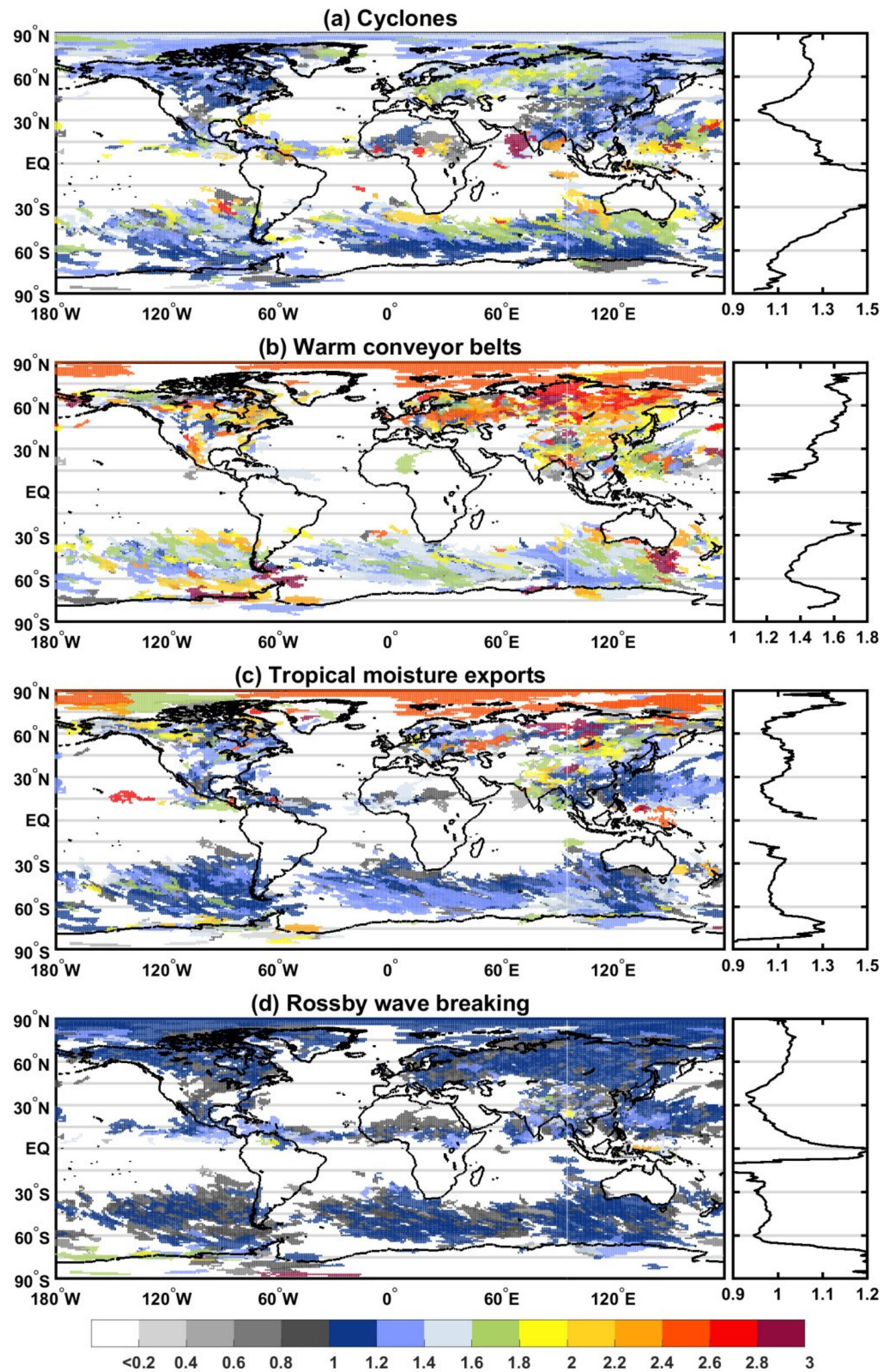
Revised Figure 11 All extreme wet season patches are coloured according to their overlapping frequency ratios with specific weather systems (relative to the climatology). Panels in the right column show the latitudinal distribution of the overlapping ratios, as zonal averages within +/- 7.5º latitude. Patches may overlap between each other; to allow higher visibility for patches with highest ratios, the overlay of the patches in all panels started from the patch with the lowest ratio.

23. Figure 12 again: Since you have a large number of patches, with central months at different times of the year, I wonder what the figure would look like if this was taken into account? So for the NH midlatitudes, you could make two figures – one for extreme patches with central month in winter, and one for summer. This would surely help to answer the question of whether seasonal extremes are caused by the same mechanisms in different times of the year in the same location. Saying this I realise that I am suggesting making things even more complex despite previously suggested less complexity. However, I think this would be a very interesting addition.

Thank you for the suggestion. We agree that such a procedure would further complicate the presentation of the results and would slightly escape the purpose of section 6 to provide a compact global overview of the relationship between weather systems and patches. But we also agree that performing the same analysis separately for DJF, MAM, JJA and SON provides an interesting perspective and a clearer impression of the monthly distribution of the patches per weather system. We therefore include these figures in this reply document (see next 4 pages), but we don't include them in the paper.



As in revised Fig. 11 in the paper, but here only for patches with a central date in MAM.



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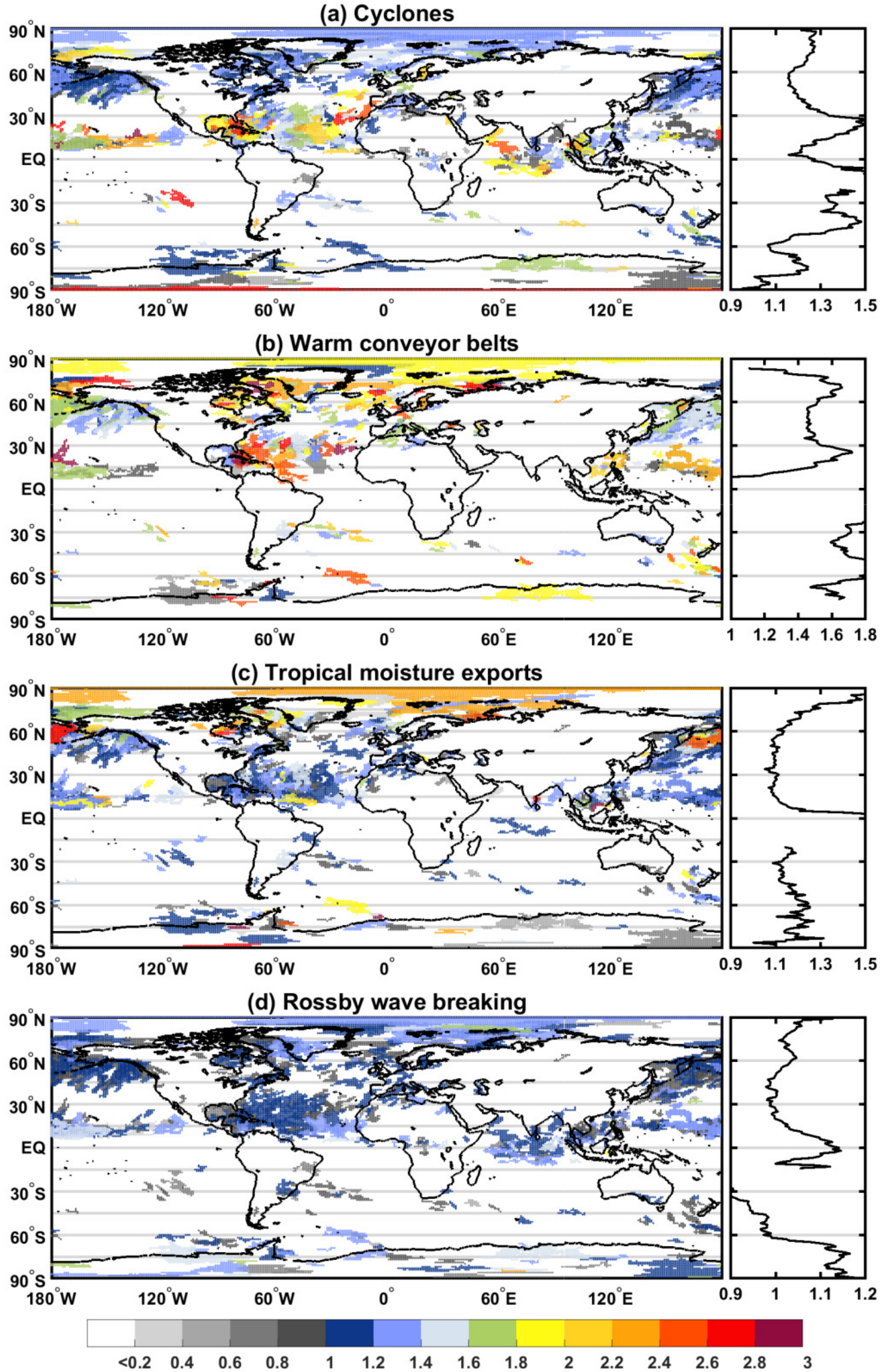

As in revised Fig. 11 in the paper, but here only for patches with a central date in SON.

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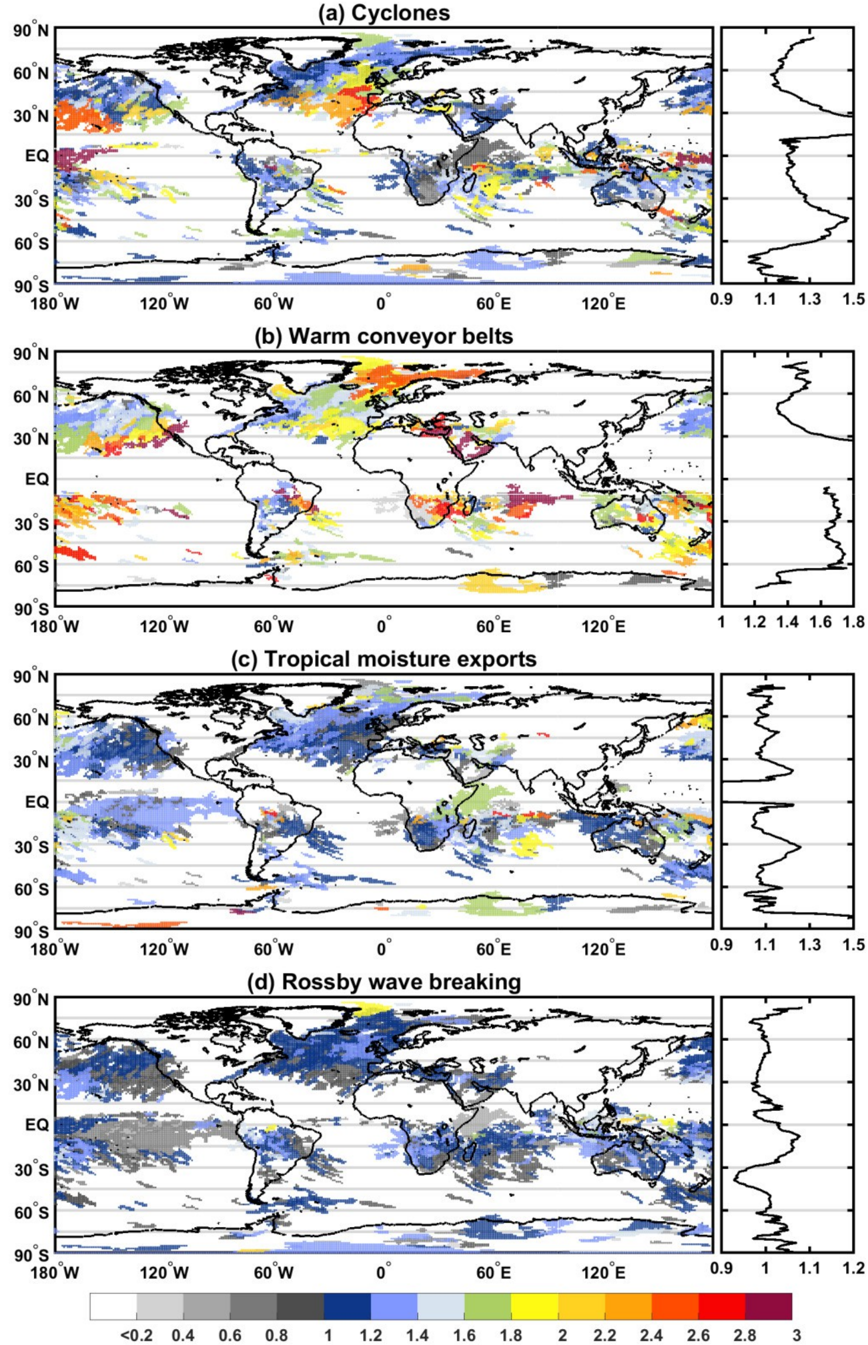


As in revised Fig. 11 in the paper, but here only for patches with a central date in DJF.

24. References: There are quite a few errors in the references, where the "running title" is given as well as the proper title: e.g. Catto et al, Feng et al, Leung et al, as well as other typos.

We apologize for these mistakes; references are now corrected.

Reviewer #2

GENERAL COMMENTS

This study provides a novel analysis of what the authors refer to as extreme precipitation seasons, defined as 90-day periods during 1979–2018 exhibiting especially large precipitation accumulations. A global climatology of these seasons is constructed and their characteristics are examined through statistical analysis. Contemporaneous global climatologies of warm conveyor belts, tropical moisture exports, breaking Rossby waves, and cyclones are employed to examine dynamical processes that con-tribute to the extreme seasons.

Overall, I found this study to be interesting and novel, and I believe that the topic fits within the scope of Weather and Climate Dynamics. The methods developed to identify extreme precipitation seasons and extreme season patches are innovative and novel, though, in my opinion, somewhat complicated. This is the first study to construct a global climatology of extreme precipitation seasons and to attempt to relate them to different types of weather systems. I believe that the study addresses important gaps in scientific understanding regarding the occurrence of extreme precipitation seasons. Despite the strengths of this study, there are a number of issues that need to be addressed with regard to the clarity of the writing, interpretation of the results, the methodology, and the background discussion.

Thank you for the careful reading of the manuscript, for the positive review and the constructive comments. They were all very helpful to improve the quality of our analysis and presentation of our results.

SPECIFIC COMMENTS

Abstract: The abstract is quite lengthy and complicated. I recommend simplifying and shortening it.

The abstract is now shorter and more direct in describing the main results.

line 43: I recommend being more specific regarding the socioeconomic impacts of these events.

The sentence has been rephrased to: "… due to their relevance for a variety of socio-economic aspects including damages to infrastructures and loss of life".

line 47: I suggest also mentioning climatological studies of relationships between PV streamers/breaking waves and precipitation extremes (e.g., Martius et al. 2006; deVries et al. 2018; Moore et al. 2019).

Done.

line 51: It is unclear what exactly you mean by 'environmental risks' in this context. Please clarify.

Sentence has been rephrased to:

"However, socio-economic impacts related to precipitation are not limited to the occurrence of single, outstanding extreme precipitation events, but they are also potentially related to accumulated precipitation on longer timescales."

line 53: Specify what impacts the hurricanes caused and the coastal regions of the United States that they affected.

We added the following:

"*… causing damages of the order of 370 billion dollars and loss of human life (Halverson, 2018; Taillie et al., 2020) ...*".

line 53–54: Note, however, that the season did include several extreme-rain-producing hurricanes.

Thank you for this information. It is now included.

line 54: Specify what the 'main impact' was? Was it prolonged regional flooding?

This phrase has been removed.

line 56: Please provide a reference for this statement.

Done.

line 111: Please explain why this model-based dataset was used. Also, please state any caveats that must be considered when using coarse-resolution model-based precipitation data.

The following was added:

"*Using a model-based instead of an observation-based dataset has the advantage of providing daily fields with continuous spatial coverage over both land and maritime areas. In addition, it assures consistent precipitation fields with atmospheric dynamics. On the other hand, global reanalyses have a rather coarse grid spacing, permitting only the analysis of precipitation related to synoptic-scale weather systems.*"

line 155–158: In my view, the authors have not provided sufficient context and background information to motivate examination of relationships to these different weather systems. This sentence is inadequate in this regard and does not fully and accurately describe the influence that these systems can have on precipitation. For instance, the authors fail to mention that PV streamers and cut-offs have also been found to be linked to strong water vapor transports and dynamical lifting. The four weather system types and their dynamical relationships to precipitation extremes should be described in more detail in the introduction section. Also, it could be worthwhile to describe inter-relationships between the four types of systems.

We agree with the reviewer that the relationship between dynamical processes and precipitation should be further detailed. We changed the paragraph accordingly and added more information:

"*All four weather systems are well known to be related to heavy precipitation. Precipitation in the vicinity of these systems is the outcome of a rather complex interaction of dynamical processes that differ between the four systems. For instance, cyclones are known to be responsible for a large part of global precipitation (Hawcroft et al., 2012; Pfahl and Wernli, 2012). The precipitation within cyclones may be attributed to a variety of processes such as deep convection in their center (e.g. in the eyewall of tropical cyclones) and to a combination of convective and stratiform precipitation along the frontal structures of extratropical cyclones (Catto and Pfahl, 2013). Especially concerning frontal structures, WCBs can be identified as distinct airstreams that produce high amounts of stratiform and in some cases also convective precipitation (Browning et al., 1973; Flaounas et al., 2017; Oertel et al., 2019). Precipitation due to WCBs affects both the central region of a cyclone and the associated fronts (Catto et al., 2013; Catto and Pfahl, 2013; Pfahl et al., 2014). TMEs foster precipitation indirectly by supplying moisture that may rain out when reaching a region with dynamical or orographic forcing for ascent. Finally, RWB can also lead to long-range transport of water vapor, impose large-scale lifting, and reduce static stability in the lower and middle troposphere, favoring thus intense precipitation (Martius et al., 2006; de Vries et al., 2018; de Vries 2020). Sometimes these weather systems occur simultaneously. For instance, RWB may lead to the formation of cyclones that in turn may include WCBs. Therefore, it is an ill-posed problem to determine the separate contribution of these weather systems to* *total precipitation. However, the objective identification of these weather systems in gridded datasets and counting their seasonal frequency of occurrence may provide interesting insights into their role in extreme wet seasons.*"

line 168: I suggest using a consistent term for the extreme seasons throughout the paper. Use either "extreme wet season" or "extreme precipitation season" but not both.

We now use extreme wet seasons throughout the text.

169–171: While I understand your justification for classifying these seasons as extreme, I am still unsure whether I agree with it. If the seasonal precipitation does not deviate much from climatology, then it really is indicative of an ordinary precipitation season. Are there ways to avoid inclusion of so many secondary seasons in the dataset? Could you use more restrictive criteria to identify secondary extreme seasons? Could you just consider the primary extreme seasons and not the secondary seasons?

The reviewer correctly identifies a major caveat of our extreme wet season identification scheme: It does not always live up to a proper statistical definition of the word "extreme". However, we deliberately choose to also identify secondary extreme wet seasons because this allows us to perform analyses which, in our opinion, yield more interesting and more relevant results than if we focused solely on primary extreme seasons. In fact, secondary seasons are almost equally important to primary seasons in terms of precipitation amount and therefore also – potentially - in terms of impacts. In addition, if we only focused on primary extreme seasons, this would render the identification of spatially coherent extreme wet season patches, and hence also their matching with weather features, less meaningful, since the patches would then each cover only a very limited number of grid points.

We agree with the Reviewer that in areas where many secondary seasons are identified, these seasons could be considered as "ordinary" (at least from the point of view of the statistical probability of occurrence). However, this also reflects an interesting, central result of our study, i.e. we identified areas where it is "hard" to get distinct periods in terms of precipitation amount. Finally, our Fig. 2a allows the reader to have insights into the likelihood of an area to experience high seasonal precipitation amounts. By identifying e.g. four extreme seasons in our 40-year dataset, in a certain grid point, this suggests that this grid point may experience high seasonal precipitation amounts roughly once every 10 years.

In some sense, by defining extreme wet seasons in this way, we trade some mathematical rigour in their definition for results that we find meaningful and relevant and that could not have been obtained otherwise. We explicitly point to this caveat of our identification scheme in section 2.1:

"*This suggests that in these regions, seasonal precipitation typically varies only by fractions rather than multiples of the climatological mean. Therefore, numerous 90-day periods fall within our definition of secondary "extreme wet seasons". These periods reach almost the same accumulated precipitation as the locally wettest period and, therefore, we choose to use the terminology "extreme wet seasons" also for these periods throughout this manuscript.*"

line 178: Perhaps insert "and occur most frequently" after "most intense"?

Done.

line 184: "This suggests..." I do not see how a lack of a sharp land–sea distinction itself suggests that a given region is influenced by atmospheric rivers and cyclones. It would be more precise to say that the lack of a distinction suggests that a region is influenced by landfalling systems originating over the ocean, such as extratropical cyclones and atmospheric rivers.

Corrected as suggested.

line 194–197: Apologies for my confusion, but I am having trouble reconciling this sentence with the previous sentence. If only results for primary seasons are presented, then how can there be multiple extreme seasons at a given grid point.

Thank you for the careful reading and apologies for this typo. Indeed, Fig. 4 does not include any secondary seasons. It is now corrected.

line 222: "arid areas": I suggest providing specific examples of these areas to aid the reader.

Figure 4 also shows the average annual precipitation. So we added the following: "... occurs rarely (outlined by dashed contours in all panels of Fig. 4)".

line 225: "climatologically wet regions": I suggest providing specific examples of these regions to aid the reader.

We added the following:

"*... climatologically wet regions (such as in the tropics, within the solid contours of Fig. 4).*"

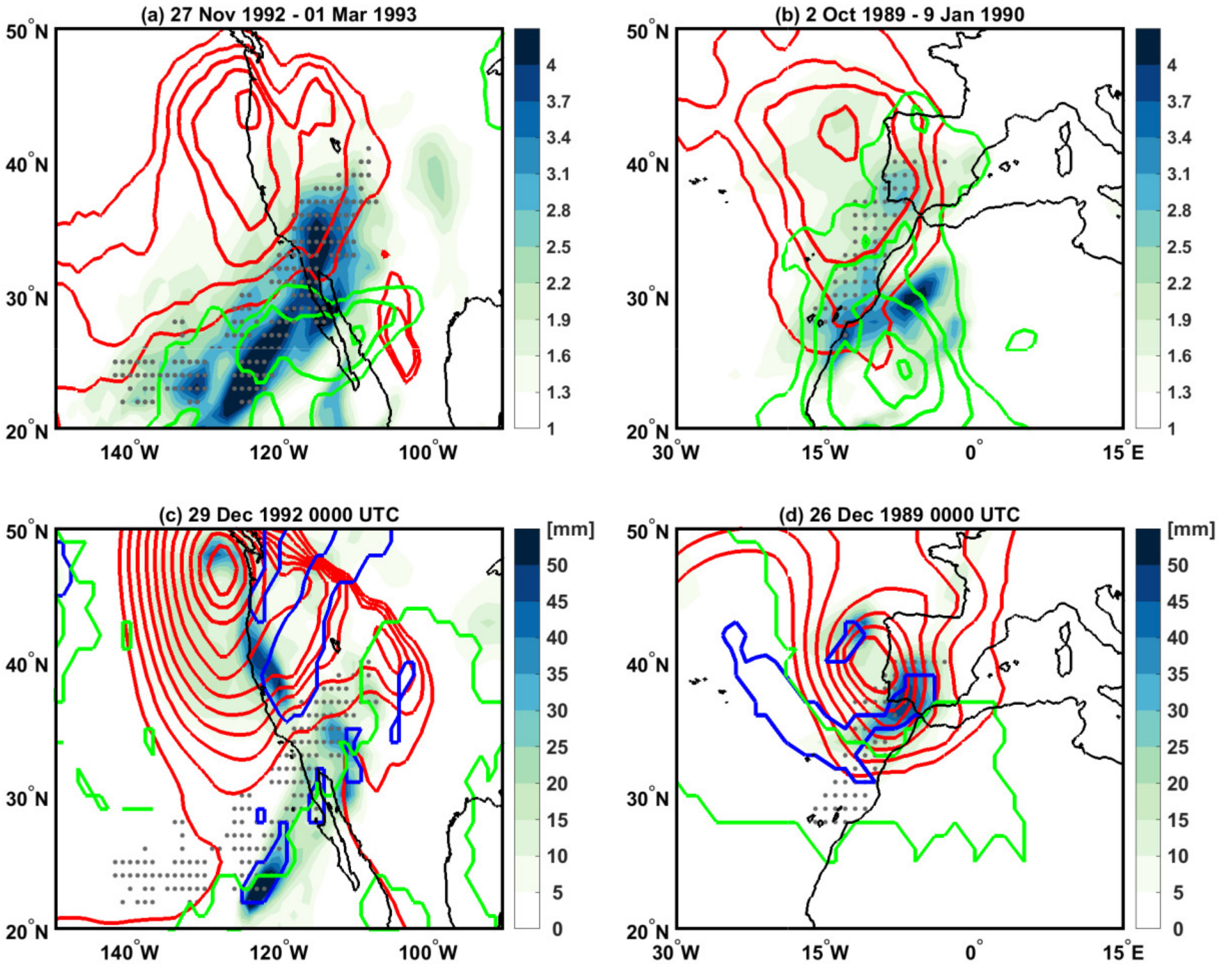
line 273: Please provide references for the 2010 and 2017 hurricane seasons.

References to Beven and Blake (2015) and Taillie et al. (2020) were added.

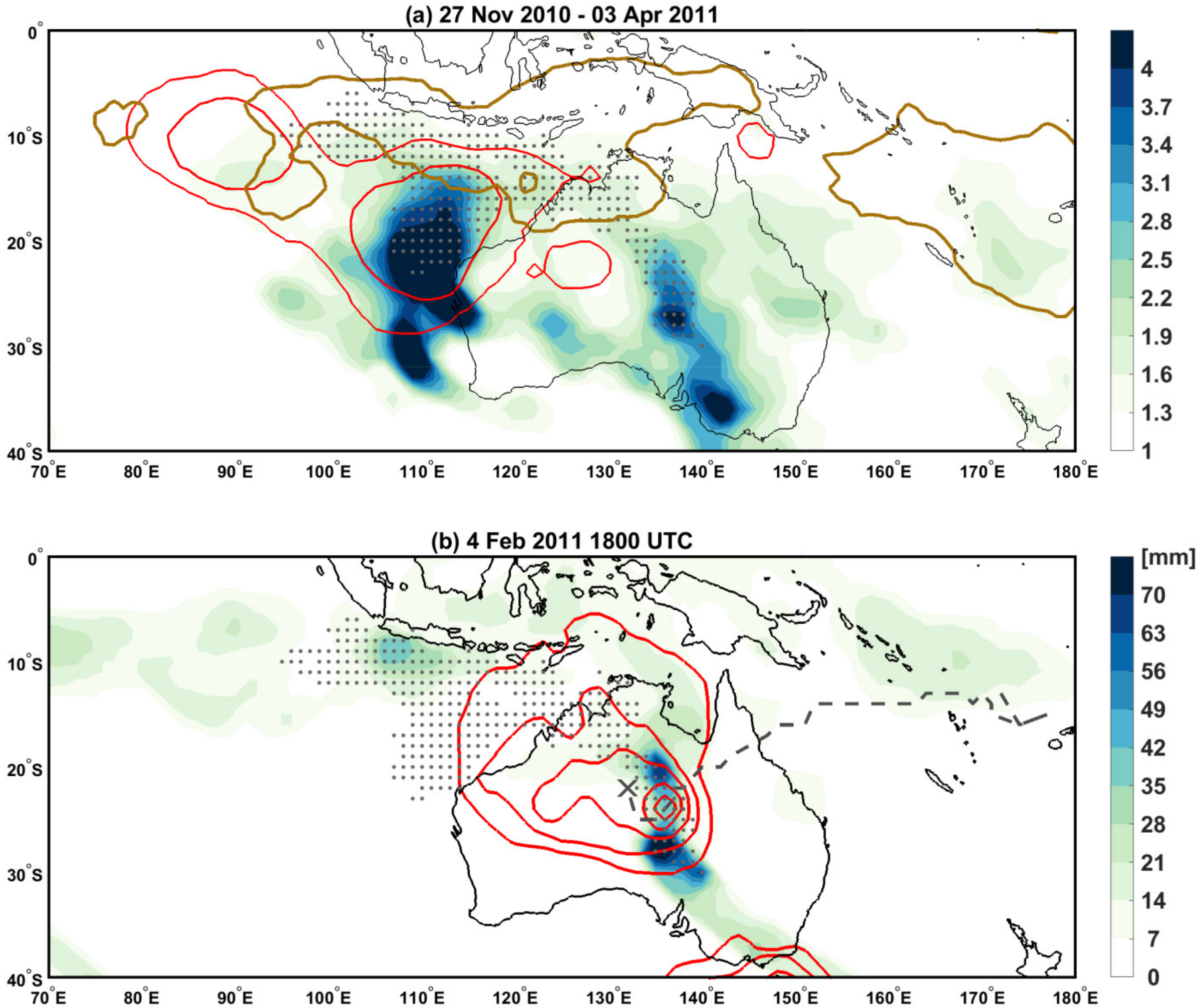
line 351: It is not clear to me how unusual the frequencies of cyclones, streamers, and TMEs depicted in Figs. 8 and 9 are for those regions and seasons. It would be helpful to compare the feature frequencies to the climatological frequencies for the timeperiods, as was done in Fig. 10.

Thank you for this comment. Also in response to a comment from the first Reviewer, we have revised section 5. To ease the reader, we now present three cases instead of four, excluding the monsoon example (Fig. 11 in the original submission).

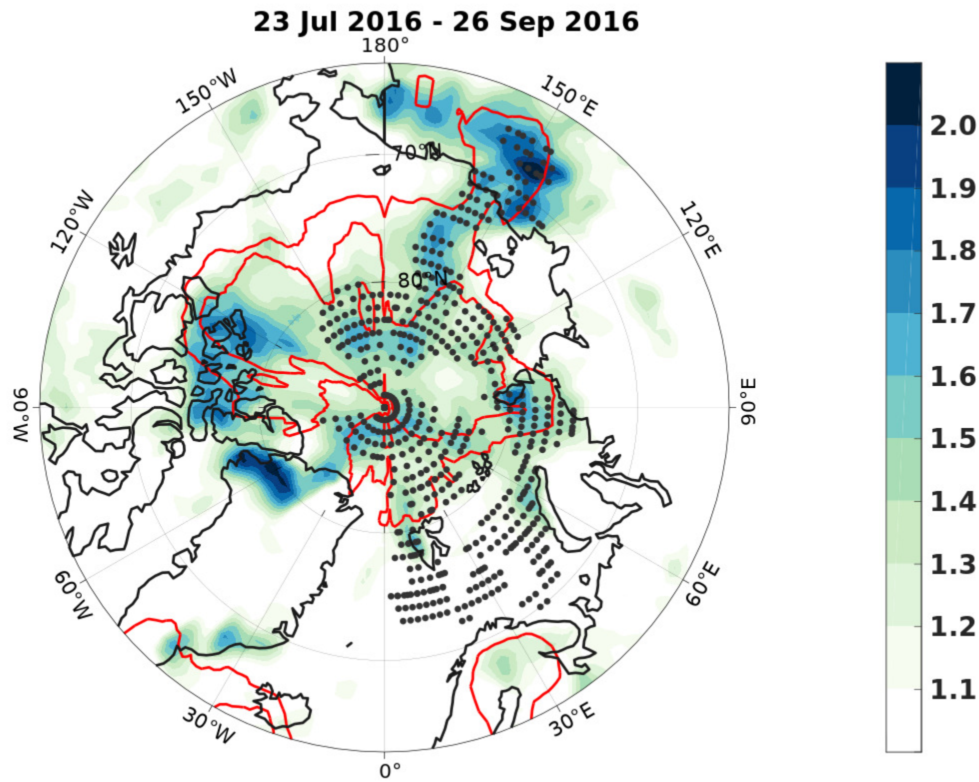
Figures 8, 9 and 10 have been revised as suggested and the text in section 5 has been adapted to the new figures. Here below follow the new figures showing ratios of seasonal precipitation and frequency anomalies with respect to climatology for the occurrence of weather features. In addition, Figs. 8 and 9 also include examples of case studies of high amounts of daily precipitation.



Revised Figure 8 (a) Ratio of accumulated precipitation during the period 27 November 1992 to 1 March 1993 with respect to climatological values for the same time period (in colour) for an extreme wet season patch affecting the US west coast (dotted area). Red (green) contours show areas with positive anomalies of cyclone (TME) occurrences with respect to climatology. Contours start from 5% and have a 5% of interval. **(b)** as **(a)** but for the period 2 October 1989 to 9 January 1990 for an extreme wet season patch affecting the Iberian Peninsula (dotted area). **(c)** 24-hour accumulation of precipitation from 1200 UTC 28 December 1992 to 1200 UTC 29 December 1992 (in colour). Red contours show sea level pressure at 0000 UTC 29 December 1992 (starting from 1015 hPa and with a step of -3 hPa). Green contours show areas with TMEs and blue contours shows areas with WCB ascent. **(d)** as in **(c)** but at 0000 UTC 26 December 1989.



Revised Figure 9 (a) Ratio of accumulated precipitation during the period 27 November 2010 to 3 April 2011 with respect to climatological values for the same time period (in colour) for an extreme wet season patch affecting Australia (dotted area). Red (green) contours show areas with positive anomalies of cyclone (RWB) occurrences with respect to climatology (shown are anomalies of 10 and 20% for cyclones and 20% for RWB). **(b)** 24-hour accumulation of precipitation from 1800 UTC 3 February to 1800 UTC 4 February 2011 (in colour). Red contours show sea level pressure at 1800 UTC 4 February 2011 (starting from 1006 hPa and with steps of -2 hPa). The grey dashed line shows the track of tropical cyclone Yasi, while its position of cyclolysis is represented by the cross symbol.



Revised Figure 10 Ratio of accumulated precipitation during the period 23 July 2016 to 26 September 2016 with respect to climatological values for the same time period (in colour). Red contours show areas with positive anomalies of cyclone occurrences with respect to climatology (shown are contours of 5 and 10%). The spatial extent of the patch is represented by the dotted area.

line 363–364: "However, the two..." It is unclear to me what the purpose of this sentence is.

It has been rephrased to: "However, the two exemplary cases in Figs. 8c and 8d also show... "

line 364–365: "The synergy..." The meaning of this statement is ambiguous to me. Which processes are you referring to?

It has been rephrased to: "The synergy of cyclones and WCBs is responsible for classifying these periods as extreme wet seasons."

line 365: "Finally, most..." Mention that this statement applies specifically to the 1992–1993 event.

This phrase has been removed.

line 365–367: "However, this comes..." What is the basis for this statement? Please provide a supporting reference.

This phrase has been removed.

line 373: “In this region...” This is not true. Cyclones can and do occur at these latitudes, as clearly depicted in Fig. 9.

It has been rephrased to: "... a region where Coriolis forces are too weak to favour cyclogenesis."

line 373–374: “However, RWB...” A figure reference is needed in this sentence.

Done.

line 374: By "upper-tropospheric systems" do you mean elongated PV streamers associated with RWB? If so, consider saying "The upper-level PV streamers resulting from the events". Upper-level is more accurate than upper-tropospheric here given that these systems are defined as narrow filaments of stratospheric high-PV air.

Changed as suggested.

line 389: The anomalous warmth could also reflect frequent poleward excursions of warm, moist air into the Arctic that supported the precipitation within the patch.

This is a very interesting suggestion. However, failing to find past studies to support this statement we chose not to add it in the paper.

line 392: “probably reflect...” this assertion does not appear to be supported by any evidence.

The phrase is changed to:

"*Evidently, such conditions can lead to extreme wet seasons in the eastern Arctic and are similar to the ones leading to a rainier future regime in the Arctic region (Bintanja, 2017).*"

line 416: What do you mean by “the largest part of the world”?

This phrase has been changed to:

"*Most latitudes except in the tropics...*"

line 417: Does this imply that the cyclone climatology used in this study also includes tropical cyclones and other tropical low pressure systems in addition to extratropical cyclones? Is there any distinction made in the climatology between extratropical and tropical systems?

We make no distinction between tropical, subtropical or extratropical cyclones. We included the following:

"*The origin of these maxima cannot be attributed clearly to either tropical, subtropical or extratropical cyclones. Nevertheless, Fig. 3 shows that these regions experience their extreme seasons in the colder months of the year and thus it is rather unlikely that tropical cyclones may contribute to their formation.*"

line 422–423: I find this sentence confusing. Which result is in accordance with Pfahl and Wernli (2012)? Also, it is a sentence fragment.

The phrase has been changed to:

“*This result suggests that cyclones occurring equatorward of the climatological storm tracks are a key ingredient for extreme wet seasons since they trigger anomalously frequent precipitation extremes in these regions (see also Pfahl and Wernli 2012).*”

line 430: it would be more dynamically accurate to say “baroclinic zones associated with cyclones” instead of “cyclones’ frontal surfaces”

The phrase has been deleted.

line 437: “physical characteristics” is vague. Please specify the physical characteristics that are relevant in this context.

"Physical characteristics" has been deleted.

line 443–444: “Therefore, TMEs...” This statement strikes me as erroneous. Can you cite a study that supports this claim? My understanding is that a TME will only support heavy precipitation where it encounters a region of strong ascending motion; thus, TMEs should not be expected to produce high amounts of precipitation whenever they reach higher latitudes but rather only under certain circumstances.

Indeed, we meant that TMEs do not trigger convection, but rather favour the production of higher amounts of precipitation. The phrase has been changed to:

"*Therefore, TMEs are expected to favour higher amounts of precipitation whenever they reach areas of strong ascending motion in higher latitudes.*'

line 448–449: “Occasionally, TMEs...” I find this sentence somewhat confusing. Please rephrase more clearly.

Phrase has been changed to:

"*Occasionally, TMEs contribute to the formation of extreme seasons in the Arctic, but the high ratios in this region (Fig. 12c) result from few events during the extreme seasons and even fewer in the climatology.*"

line 454–455: I do not entirely follow this reasoning. The ratios shown in Fig. 12 do not necessarily indicate the strength of the contribution of a given type of weather system. They only indicate the degree to which weather system frequencies deviate from climatology during extreme precipitation seasons. It seems to me that it is still possible for systems to produce large portions of the precipitation during extreme seasons even if their frequencies do not deviate substantially from climatology.

We agree that ratio of occurrence is not necessarily correlated with the precipitation amount. To avoid confusion, we removed the previous sentence so that lines 454-455 do not come as a natural continuation of the physical relationship between RWB and the production of precipitation. The removed lines have been shifted to section 2.3.

line 457: It would be more precise to say “PV streamers” rather than “filaments”

Done.

line 459: What do you mean by “RWB into the tropics”? Perhaps it would be more accurate to say “extension of PV streamers into the tropics”.

Done.

line 461–463: "It is noteworthy that..." I really do not understand this sentence. Please clarify.

It has been changed to:

"Nevertheless, other weather systems or conditions than RWBs, cyclones and WCBs might be also involved in forming daily precipitation extremes in the tropics and thus be responsible for the formation of extreme seasons (e.g. a very strong ITCZ or warmer sea surface temperatures)."

line 463–464: "Finally, the..." This sentence does not make sense to me.

Phrase has been changed to:

"Finally, in polar latitudes there are relatively high frequency ratios of RWB that may be directly related to the high frequency ratios of WCBs in same areas (Fig. 12b), especially in the Southern Hemisphere."

line 464–466: "Indeed, WCBs..." I do not understand how this sentence connects with the preceding discussion in this paragraph.

Changing the previous phrase and simplifying this one, we believe that now the connection is clearer.

line 488: It seems to me, based on the results in Figs. 8–11, that large patches can also result from synoptic-scale weather systems, such as extratropical cyclones and RWB. This should also be mentioned here.

Done.

line 499–500: The streamers that form in connection with wave breaking tend to be part of baroclinic waves that are tilted with height. Thus, widespread heavy precipitation produced in association with wave breaking is often displaced downstream and spatially separated from the upper-level streamer. The approach for linking RWB to the extreme precipitation seasons in this study does not appear to directly account for this fact.

Thank you for this comment. In this study we restrict ourselves to simply quantifying how often weather systems co-occur with the patches during extreme wet seasons, relative to their climatological occurrence in the respective regions. We agree with the reviewer that it is a challenge to quantify the exact amount of precipitation caused by weather systems, especially RWB. By diagnosing the co-occurrence of weather features and patches of extreme wet seasons we expect to consider a large part of precipitation in our patches that may extend beyond the grid points that define RWB features. The causation in our arguments is based on the many previous studies that show in much more detail how the four weather systems are related to precipitation, as now explained in section 2.3 (in response to your comment on lines 155-158 of the original submission).

We are now more explicit on how we calculate the co-occurrence ratios, including the following at the end of section 2.3:

"A common framework has been applied to quantify the co-occurrence of these weather systems and extreme season patches. This co-occurrence is defined for each patch as the number of grid points of the patch that overlap with a specific weather system (note that all our weather systems are defined as two-dimensional objects), averaged during the core period (see Section 4.2) of the patch. We then show ratios of this co-occurrence during the core period of the considered extreme season (e.g., from 10 Feb to 22 May 1993) with respect to the climatological co-occurrence (40-year average for periods from 10 Feb to 22 May). A more detailed method to quantify co-occurrence would require a direct attribution of precipitation to each weather feature, as done, e.g., by Moore et al. (2019) and de Vries (2020). Nevertheless, this would increase the complexity,

since several weather systems may interact to synergistically produce high precipitation amounts, as explained above. Our method thus simply quantifies the co-occurrence of weather systems and extreme wet seasons in the regions identified as wet season patches. Nevertheless, due to the direct relevance of the four weather systems for precipitation, our approach provides insight into the role of weather systems in forming extreme seasons."

TECHNICAL CORRECTIONS

line 43: “always” -> “long”

Done.

line 46: remove “a high number of”

Done.

line 57: “The factors...” Perhaps start a new paragraph here?

Done.

line 72: “aggregation” -> “accumulation”

Done.

line 81: “The grand” -> “A large”

Done.

line 84: “state of the art” -> “scientific understanding of this topic”

Done.

line 90: “this chain of events” -> “the chain of events governing precipitation”

Done.

line 93–94: I suggest inserting citations immediately after the corresponding phenomenon in the list. For instance, "cyclones (Pfahl and Wernli 2012), fronts (Catto et al. 2012), warm conveyor belts (Pfahl et al. 2014)..."

Done.

line 98: would "the frequency and intensity of the precipitation it produces" be more precise than “its frequency and its intensity”?

Done.

line 175: “mainly” -> “predominantly”

Done.

line 178: “me” -> “be”

Done.

line 179: “Indian Ocean)”

Done.

line 186: insert “evident in” after “are”

Done.

line 193: insert “results for” after “Only”

Done.

line 213: Insert “the number of” before “ratio of”

Done.

line 222: “few more” -> “a small increase in the number of”

Done.

line 232: “the grand” -> “a large”

Done.

line 272: “depict” -> “correspond to”

Done.

line 273: “includes the track of” -> “corresponds to”

Done.

line 352: remove “is” after “It”

Done.

line 360: “highlight the important link” -> “suggest links”

Done.

line 361–363: delete “Pfahl et al. (2014) showed that” and insert the (Pfahl et al. 2014)at the end of the sentence.

Done.

line 377: “make” -> “made”

Done.

line 381: insert “necessarily” after “should not”; replace “in the sense that” with “because”; replace “is due” with “can be due”

Done.

line 416: “formation” -> “occurrence”

Done.

line 439: “the scarcity” -> “climatological infrequency”

Done.

line 440: “contributes to” -> “can result in”

Done.

line 443: “to moist plumes that originate” -> “transports of moist air”

Done.

line 487: “methodology” -> “method”

Done.

line 492–493: “considering their...” This is awkwardly worded. Please rewrite.

Sentences were rephrased to:

"Four weather systems, known to be related to (extreme) daily precipitation events, were used to understand the role of synoptic-scale dynamics in forming extreme wet seasons. These systems were objectively identified in the 40-year dataset in order to quantify their overlap with the extreme wet season patches."

line 495: insert “, respectively” after “tropics”

Done.

line 512: “strongly” -> “highly”

Done.

Figure 2: “rainfall” should be changed to “precipitation”

Done.

Figure 4: Recommended edit to the caption: “and (b) the ratio of the number”

Changed as suggested.

Figure 5: What is a precipitable day?

Changed to "wet days".

Figure 11: The panels should be labelled (a) and (b).

Done.

Figure 12: It is unclear to me what you mean by “illustration started from the patch presenting the lowest ratio”

The last sentence of the caption was changed to:

"Patches may overlap between each other; to allow higher visibility for patches with highest ratios, the overlay of the patches in all panels started from the patch with the lowest ratio."

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Extreme wet seasons – their definition and relationship with synoptic scale weather systems

Emmanouil Flaounas[1], Matthias Röthlisberger[1], Maxi Boettcher[1], Michael Sprenger[1] and Heini Wernli[1]

[1]Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland

Correspondence to: Emmanouil Flaounas (emmanouil.flaounas@env.ethz.ch)

Abstract.

An extreme aggregation of precipitation on the seasonal timescale, leading to a so-called extreme wet season, can have substantial environmental and socio-economic impacts. This study has a twofold aim: first to identify and statistically characterize extreme wet seasons around the globe, and second, to elucidate their relationship with specific weather systems.

Extreme wet seasons are defined independently at every grid point of ERA-Interim reanalyses as the consecutive 90-day period with the highest accumulated precipitation in the 40-year period of 1979-2018. In most continental regions, the extreme seasons occur during the warm months of the year, especially in the mid-latitudes. Nevertheless, colder periods might be also relevant, especially in coastal areas. All identified extreme seasons are statistically characterized in terms of climatological anomalies of the number of wet days and of daily extreme events. Results show that daily extremes are decisive for the occurrence of extreme wet seasons in regions of frequent precipitation, e.g. in the tropics. This is in contrast to arid regions where wet seasons may occur only due to anomalously frequent wet days. In the subtropics and more precisely within the transitional zones between arid areas and regions of frequent precipitation, both an anomalously high occurrence of daily extremes and of wet days are related to the formation of extreme wet seasons.

A novel method is introduced to define the spatial extent of regions affected by a particular extreme wet season, and to relate extreme seasons to four objectively identified synoptic-scale weather systems, which are known to be associated with intense precipitation: cyclones, warm conveyor belts, tropical moisture exports and breaking Rossby waves. Cyclones and warm conveyor belts contribute particularly strongly to extreme wet seasons in most regions of the globe. But interlatitudinal influences are also shown to be important: tropical moisture exports, i.e., the poleward transport of tropical moisture, can contribute to extreme wet seasons in the mid-latitudes, while breaking Rossby waves, i.e., the equatorward intrusion of stratospheric air, may decisively contribute to the formation of extreme wet seasons in the tropics. Three illustrative examples provide insight into the synergetic effects of the four identified weather systems on the formation of extreme wet seasons in the mid-latitudes, the Arctic and the (sub-)tropics.

An extreme aggregation of precipitation on the seasonal timescale, leading to a so-called extreme wet season, can have substantial environmental and socio-economic impacts. In contrast to extreme precipitation events on hourly to daily

timescales, which are typically caused by single weather systems, an extreme wet season may be attributed to a combination of different and/or recurring weather systems. In fact, extreme wet seasons may be formed by almost continuously occurring moderate events, or by more frequent and/or more intense short-duration extreme events, or by a combination of these scenarios. This study aims at identifying and statistically characterizing extreme wet seasons around the globe, and elucidating their relationship with specific weather systems.

To define extreme wet seasons, we used 40 years (1979-2018) of ERA-Interim reanalyses. Primary extreme seasons were defined independently at every grid point as the consecutive 90-day period with the highest accumulated precipitation. Secondary extreme seasons were also considered, if accumulated precipitation amounts to at least 90% of the precipitation in the primary season at the same grid point. A high number of secondary extreme seasons was found for instance in the extratropical storm tracks, suggesting that these regions are less likely to experience an exceptional amount of precipitation in a particular 90-day period. In most continental regions, the extreme seasons occur during the warm months of the year, especially in the mid-latitudes. Nevertheless, colder periods might be also relevant to extreme seasons within the same continent, especially in coastal areas. All identified extreme seasons were statistically characterised in terms of anomalies compared to the climatology of the number of wet days and daily extreme events. Results show that daily extremes are decisive for the occurrence of extreme wet seasons in regions of frequent precipitation, e.g. in the tropics. In contrast, e.g., in arid regions where wet days are scarce, extreme seasons may occur only due to anomalously high numbers of wet days. In the subtropics and more precisely within the transitional zones between arid areas and regions of frequent precipitation, both an anomalously high occurrence of daily extremes and wet days are related to the formation of extreme wet seasons. The spatial extent of regions affected by the same extreme wet season is variable and can reach continental scales, although the vast majority of extreme seasons is limited to scales of the order of $20x10^5$ km^2.

Finally, the relationship of extreme seasons to synoptic-scale weather systems was investigated on the basis of four objectively identified weather systems that are known to be associated with intense precipitation: cyclones, warm conveyor belts, tropical moisture exports and breaking Rossby waves. A grid-to-grid association of these weather systems to daily precipitation allows quantifying their role for extreme wet seasons. In particular, cyclones and warm conveyor belts contribute strongly to extreme wet seasons in most regions of the globe. But interlatitudinal influences are also shown to be important: tropical moisture exports, i.e., the poleward transport of tropical moisture, can contribute to extreme wet seasons in the mid-latitudes, while breaking Rossby waves, i.e., the equatorward intrusion of stratospheric air, may decisively contribute to the formation of extreme wet seasons in the tropics. Four illustrative examples provide insight into the synergetic effects of the four identified weather systems on the formation of extreme wet seasons in the Arctic, the mid-latitudes, Australia, and the tropics.

1 Introduction

This study focuses on extreme precipitation, however not on short timescales of single weather systems like thunderstorms or cyclones, but on the seasonal timescale. The analysis of extreme precipitation events on timescales of hours to a few days has long been a centerpiece of weather and climate research ~~due to their relevance for a variety of socio-economic sectors.~~due to their relevance for a variety of socio-economic aspects including damages to infrastructures and loss of life. Indeed, many studies investigated single extreme precipitation events to identify the key dynamical and physical processes involved (e.g., Doswell et al., 1998; Massacand et al., 1998; Delrieu et al., 2005; Holloway et al., 2012; Moore et al., 2012; Winschall et al., 2012; Flaounas et al., 2016). In addition, climatological studies quantified the relationship of extreme precipitation events with specific synoptic-scale flow systems like cyclones (Pfahl and Wernli, 2012), fronts (Catto and Pfahl, 2013), and warm conveyor belts (Pfahl et al., 2014). Finally, another important strand of research addressed the future evolution of extreme precipitation events in a changing climate, using a plethora of simulation ensembles, reanalysis datasets and observations (e.g., Easterling et al., 2000; Shongwe et al., 2011; Pfahl et al., 2017).~~ However, environmental risks are not limited to the occurrence of single, outstanding extreme precipitation events, but they are also potentially related to precipitation on longer timescales.~~ However, socio-economic impacts related to precipitation are not limited to the occurrence of single, outstanding extreme precipitation events, but they are also potentially related to accumulated precipitation on longer timescales. For instance, the costliest, hyperactive North Atlantic hurricane season of 2017 had a significant impact on the coastal population of the US due to an anomalous sequence of landfalling tropical cyclones, ~~(Halverson, 2018)~~causing damages of the order of 370 billion dollars and loss of human life (Halverson, 2018; Taillie et al., 2020). The 2017 hurricane season~~ although it~~ did not include any record-breaking intense hurricane although it included several hurricanes producing extreme precipitation.~~. The main impact was due to an anomalous sequence of landfalling tropical cyclones.~~ Another example of seasonal-scale environmental risk is the direct relationship between the seasonal rainfall over the Sahel and the epidemics of meningitis (Sultan et al., 2005). In fact, an anomalously wet African monsoon season may have a detrimental impact on public health on continental scales (Polcher et al., 2011)~~ (Sultan et al., 2005)~~.

The factors contributing to the formation of extreme seasons may not be linked directly to the anomalous occurrence of extreme events as intuitively expected. Röthlisberger et al. (2020) showed that an extreme hot or cold season may not be always provoked by the repetitive occurrence of exceptionally high or low temperatures, respectively. In contrast, an extremely warm summer ~~may also be provoked~~can also occur due to its coldest days being anomalously mild. Therefore, the seasonal distribution of weather variables plays an important role ~~to the~~for characteriz~~ation of~~ing a season. Despite ~~its~~ their high socio-economic relevance, the analysis of extreme ~~precipitation~~wet seasons has not gained high visibility in climate research so far. This study addresses this research gap and aims to contribute to a better understanding of the characteristics of extreme ~~precipitation~~wet seasons around the globe and to provide insight about the responsible weather systems.~~ In the following we refer to these seasons as extreme wet seasons.~~

The definition and identification of distinct precipitation seasons is a delicate issue and highly dependent on the region of interest. Monsoon-affected regions typically experience a clear onset date that signals the beginning of the precipitation period (Bombardi et al., 2017; 2019), while several mid-latitude areas experience more than one rainy season, or they are characterized by wet conditions year-round. On the other hand, semi-arid and arid areas do not have clearly preferred precipitation periods due to the scarcity of wet days and thus the definition of a precipitation season becomes less meaningful in these areas (Wu et al., 2007). Regardless, if a region experiences an extreme seasonal accumulation of precipitation, e.g., due to an anomalous frequency of daily extreme events, this has a potentially hazardous effect. Indeed, the above examples about hurricane and monsoon seasons illustrate that significant seasonal precipitation anomalies may be related to both an anomalous frequency and intensity of precipitation events. Depending on the region, seasonal precipitation extremes may be related to a well-defined, unique, and recurrent weather system, such as tropical cyclones, or they may be related to a variety of weather systems that occur sequentially in the considered season, favored by regional or global-scale atmospheric conditions. For instance, Davies (2015) and Röthlisberger et al. (2019) showed that the anomalously wet and stormy European winter of 2013/2014 was related to recurrent upper-tropospheric flow conditions that triggered a succession of high-impact weather systems. Climatological influences might be also important for seasonal precipitation, for instance in the Mediterranean. A large majority of precipitation in this region is due to intense cyclones (Flaounas et al., 2018), however, the intensity of cyclones and related rainfall is influenced by the North Atlantic Oscillation and the El Nino Southern Oscillation (Mariotti et al., 2002; Raible, 2007). Seasonal precipitation has been the theme of numerous studies in the past; however, in this study we add to the scientific understanding of this topic by focusing on extreme wet seasons and performing a systematic analysis of how individual weather system contribute to their occurrence.

Weather systems on different spatial scales may interact to give rise to extreme wet seasons. For instance, synoptic-scale atmospheric conditions may favor the occurrence of andor intensify mesoscale weather systems, which in turn may lead to variable amounts of precipitation depending on their physical characteristics, e.g. water vapor content, precipitation efficiency, etc. It is a scientific challenge to delineate and objectively identify all links in the chain of events governing precipitation in climatological datasets. As mentioned above, several studies have quantified the role of specific weather systems such as cyclones (Hawcroft et al., 2012; Pfahl and Wernli, 2012; Flaounas et al., 2016), fronts (Catto et al., 2012), warm conveyor belts (Pfahl et al., 2014), tropical moisture exports (Knippertz and Wernli, 2010), troughs, cut-off systems, and breaking Rossby wave (e.g., Martius et al., 2006; de Vries et al., 2018; Moore et al., 2019; de Vries, 2020) for precipitation on regional and global scales. Nevertheless, it is an open question whether these weather systems occur successively or act synergistically to form an extreme wet season in a certain region. Moreover, it is an open question whether extreme wet seasons may be produced by more frequent daily extreme events, more intense daily extremes, or by higher persistence of moderate rainfall – or a combination of these options. In fact, the aggregated contribution of a weather system to seasonal precipitation may be statistically characterized by the frequency and intensity of the precipitation it produces (e.g. Toreti et al., 2010; Moon et al., 2019). This study uses these concepts to statistically characterize extreme wet seasons, to address their spatial coherence, and to quantify the contributions of specific weather systems. In this way, we aim to provide novel insight into the relationship between the statistical characteristics of extreme wet seasons and their dynamical origin.

In the next section, we present the datasets and methods used to define extreme wet seasons and to objectively identify the contributing weather systems. In section 3, we perform a statistical approach at every grid point to characterize extreme wet seasons by the number of daily extreme precipitation events and by the number of wet days that occur in this season. The spatial coherence of extreme wet seasons is then analyzed in section 4. Section 5 shows examples of the complexity of how different weather systems contribute to extreme wet seasons and section 6 provides a global overview of these contributions. Finally, Section 7 provides the summary and conclusions.

2 Dataset and methods

2.1 Identification of extreme wet seasons

We use daily accumulated precipitation fields from the ERA-Interim (ERAI) reanalysis of the European Centre for Medium-Range Weather Forecasts (Dee et al., 2011) for the period of 1979-2018, on a global grid with 1° spacing in both longitude and latitude. Using a model-based instead of an observation-based dataset has the advantage of providing daily fields with continuous spatial coverage over both land and maritime areas. In addition, it assures consistent precipitation fields with atmospheric dynamics. On the other hand, global reanalyses have a rather coarse grid spacing, permitting only the analysis of precipitation related to synoptic-scale weather systems. Forty years ~~This~~ is a rather short ~~climatological~~ period to analyze extreme wet seasons climatologically, ~~providing~~ with roughly 40 precipitation seasons in most regions of the globe (Bombardi et al., 2017). Our overarching objective is to provide insights into their link with weather systems. Therefore, "extremeness" is used in this study as a term with an impact-related content, rather than to characterize wet seasons statistically as periods with a low probability of occurrence. Extreme wet seasons (in the following just referred to as extreme seasons) have been defined separately at every grid point, as the consecutive 90-day period with the highest amount of accumulated precipitation in the 40-year period of 1979-2018. Prior to identifying extreme seasons, daily precipitation amounts less than 1 mm have been set to zero. This was done to avoid characterizing days with ~~as wet days~~ very low model-produced accumulations as wet days. Choosing any consecutive 90-day period instead of the standard astronomical definition of seasons was motivated by variations of well-defined ~~rainy~~ precipitation seasons at different latitudes (Bombardi et al., 2019). However, considering only the top 90-day period of accumulated precipitation risks to neglect other periods that present almost equally ~~-~~high precipitation amounts. Such periods ~~are~~ fall within the scope of this study, ~~i.e.~~which is to ~~relate weather systems~~characterize seasons with ~~anomalously high~~potentially high-impact ~~seasonal~~ accumulations of precipitation. Therefore, secondary extreme seasons have been also considered at every grid point even if these seasons may not be statistically considered as extreme. ~~These secondary seasons~~They correspond to 90-day periods with accumulated precipitation exceeding 90% of the precipitation in the primary extreme season at the same grid point. All primary and secondary extreme seasons at one grid point were forced to not overlap in time. The result of this first step is, for every grid point, a list with the primary extreme season and a number of~~between zero and 28~~ secondary extreme seasons (zero to 28 with a median of XX). Each of these seasons is characterized by their time period and precipitation amount. All results in section 3 are based on this dataset.

2.2 Spatial and temporal coherence of extreme ~~precipitation~~wet seasons

After identifying primary and secondary extreme seasons at every grid point, we ~~defined~~ examine their spatial coherence. To this end, we consider that two neighboring grid points are experiencing the same extreme season if their corresponding 90-day periods overlap temporally by at least 75%, i.e. if they have at least 68 days in common. Figure 1 illustrates an example of our approach for an idealized one-dimensional space-time grid, where extreme seasons with differing time periods have been identified at six neighboring grid points. According to our methodology, the extreme seasons identified at grid points 1, 2 and 3 fulfil the time overlap criterion and form a spatially coherent extreme season, which we refer to as a "patch" in the following. Analogously, grid points 4 and 5 form an extreme season patch, but this patch is distinct from the patch formed by grid points 1-3. Note that as an effect of this approach, a patch eventually extends over a time period that is longer than 90 days; we will address this issue in detail in section 4.2. Because every grid point may have several secondary extreme seasons, the same grid point can be part of several patches. To identify all possible patches, we repeated the procedure illustrated in Fig. 1 using as starting point every identified extreme season at every grid point (the primary and any secondary ones). This resulted in a~~n extremely~~ high number of patches, with many (almost) identical patches. After removing duplicates, i.e. patches with at least 90% of common points in space and time, we ended up with a total of 3734 patches, each representing a spatially and temporally coherent extreme season. For all patches, the coordinates of their grid points and their time periods are available as supplementary material.

2.3 Relating weather systems with extreme seasons

The relationship between extreme wet season patches and individual weather systems is examined for cyclones, warm conveyor belts (WCB), tropical moisture exports (TME), and events of Rossby wave breaking (RWB). All these weather systems are objectively identified in the 40-year ERAI dataset using six-hourly atmospheric fields and the methods described in Sprenger et al. (2017) and references therein. In essence, at every 6-hourly time step of ERAI and for every weather system, the algorithms identify spatially coherent clusters of grid points that belong to the same weather system, very much like the patches of the extreme wet seasons. Table 1 provides a summary of the identification criteria and algorithms used. ~~We consider as RWB either a filamentary streamer or detached cut-off system of stratospheric potential vorticity. All four weather systems are known to be related to heavy precipitation, either directly, e.g. by reducing static stability and favouring convection, as in the case of stratospheric potential vorticity streamers and cut-offs or by strong lifting of moist air as in~~

WCBs; or indirectly by favouring dynamical processes that synergistically lead to spatially organised precipitation (cyclones or TMEs). A common framework has been applied to quantify the contribution of these weather systems to extreme season patches by considering the spatial overlap of the weather systems and of the patches, as explained further in section 4.2.

All four weather systems are well known to be related to heavy precipitation. Precipitation in the vicinity of these systems is the outcome of a rather complex interaction of dynamical processes that differ between the four systems. For instance, cyclones are known to be responsible for a large part of global precipitation (Hawcroft et al., 2012; Pfahl and Wernli, 2012). The precipitation within cyclones may be attributed to a variety of processes such as deep convection in their center (e.g. in the eyewall of tropical cyclones) and to a combination of convective and stratiform precipitation along the frontal structures of extratropical cyclones (Catto and Pfahl, 2013). Especially concerning frontal structures, WCBs can be identified as distinct airstreams that produce high amounts of stratiform and in some cases also convective precipitation (Browning et al., 1973; Flaounas et al., 2017; Oertel et al., 2019). Precipitation due to WCBs affects both the central region of a cyclone and the associated fronts (Catto et al., 2013; Catto and Pfahl, 2013; Pfahl et al., 2014). TMEs foster precipitation indirectly by supplying moisture that may rain out when reaching a region with dynamical or orographic forcing for ascent. Finally, RWB can also lead to long-range transport of water vapor, impose large-scale lifting, and reduce static stability in the lower and middle troposphere, favoring thus intense precipitation (Martius et al., 2006; de Vries et al., 2018; de Vries 2020). Sometimes these weather systems occur simultaneously. For instance, RWB may lead to the formation of cyclones that in turn may include WCBs. Therefore, it is an ill-posed problem to determine the separate contribution of these weather systems to total precipitation. However, the objective identification of these weather systems in gridded datasets and counting their seasonal frequency of occurrence may provide interesting insights into their role in extreme wet seasons.

A common framework has been applied to quantify the co-occurrence of these weather systems and extreme season patches. This co-occurrence is defined for each patch as the number of grid points of the patch that overlap with a specific weather system (note that all our weather systems are defined as two-dimensional objects), averaged during the core period (see Section 4.2) of the patch. We then show ratios of this co-occurrence during the core period of the considered extreme season (e.g., from 10 Feb to 22 May 1993) with respect to the climatological co-occurrence (40-year average for periods from 10 Feb to 22 May). A more detailed method to quantify co-occurrence would require a direct attribution of precipitation to each weather feature, as done, e.g., by Moore et al. (2019) and de Vries (2020). Nevertheless, this would increase the complexity, since several weather systems may interact to synergistically produce high precipitation amounts, as explained above. Our method thus simply quantifies the co-occurrence of weather systems and extreme wet seasons in the regions identified as wet season patches. Nevertheless, due to the direct relevance of the four weather systems for precipitation, our approach provides insight into the role of weather systems in forming extreme seasons.

3 Statistical characterization of extreme precipitationwet seasons

Figure 2a shows the number of extreme seasons identified at each grid point, while Fig. 2b shows, as a reference, the global distribution of annual mean precipitation during the 40-year period in ERAI. Most regions, in particular most land and climatologically drier regions, show no more than one to five extreme precipitationwet seasons. However, the number of identified extreme seasons increases to 5-20 in areas where the annual precipitation amount is high, in particular in the inter-tropical convergence zone (ITCZ) and the mid-latitude storm tracks over the eastern North Pacific, the North Atlantic and in the Southern Ocean along 60ºS. This suggests that in these regions, seasonal precipitation typically varies only by fractions rather than multiples of the climatological mean. Therefore, numerous 90-day periods fall within our definition of secondary "extremely wet seasons". TIt is thus clear that in these regions our method identifies some periods that cannot be considered "extreme" from a statistical point of view, i.e., a period with a very low probability of occurrence. Yet, these periods reach almost the same accumulated precipitation as the locally wettest period and, therefore, we choose to use the terminology "extreme wet seasons" also for these periods throughout this manuscript.

Figure 3 shows the seasonality of the primary extreme seasons. Color assignment is done according to the month that includes the central date of each primary extreme season. In both hemispheres there is a clear shift in seasonality from oceanic to land regions. Over continental areas, extreme wet seasons occur predominantly during boreal and austral summer, when convection triggered by strong solar radiation becomes important (see, e.g., Rüdisühli et al., 2020, for Europe). Over mid-latitude maritime areas, the extreme seasons occur mainly in boreal and austral winter, when storm tracks are fully developed and extratropical cyclones tend to be most intense and occur most frequently. In regions where tropical cyclones occur frequently (e.g., in the Caribbean and southern Indian Ocean); the wettest seasons occur in the respective autumn season. For the Arctic, extreme seasons occur in late summer and early autumn when sea ice coverage is at its minimum, for Antarctica, however, the pattern is very heterogeneous. In the tropics, extreme seasons are most frequent during summer, following the latitudinal displacements of the ITCZ.In the tropics, extreme seasons are most frequent in regions affected by the latitudinal displacements of the ITCZ. However, Fig. 3 shows that the land-sea distinction is not equally sharp in all regions. For instance, the west coast of the US, the Iberian Peninsula and the north African coast, as well as Chile and eastern Australia all experience primary extreme wet seasons in winter. This suggests that such regions are evident in strongly influenced by landfalling systems, such as extratropical cyclones winter systems such asand atmospheric rivers and cyclones (Rutllant and Fuenzalida, 1991; Leung and Qian, 2009; Lavender and Abbs, 2012; Flaounas et al., 2017). Other exceptions from the dominant summer occurrence of extreme wet seasons over land are several regions in the Northern Hemisphere where extreme seasons occur in spring, in contrast to summer for their neighboring continental areas. This is especially observed near Iran, in the southern part of the Arabian Peninsula, and in eastern China and the eastern US. Especially for the east coast of the US, spring-time extreme seasons are plausibly conceivably related to anomalously high frequent occurrences of daily extreme precipitation events (Li et al., 2018).

Next, the extreme seasons are statistically characterized. To this aim, Fig. 4a shows the ratio of precipitation amounts during these seasons to climatological, i.e., 40-year averaged values for the same 90 days. Only results for primary extreme seasons are presented, while results are similar for secondary seasons. For instance, if a grid point experiences ~~two~~an extreme season~~s, one~~ from 10 Feb to 09 May 1991~~ and the second one from 23 Feb to 22 May 2012~~, then the value in Fig. 4a corresponds to the ratio of the total ~~average of the~~ precipitation in th~~ese two~~is specific period~~s~~ with the ~~average of the~~ precipitation in all periods in the 40 years from 10 Feb to 09 May~~ and 23 Feb to 22 May~~. By definition, extreme seasons have ~~higher~~ larger precipitation amounts than the climatology and therefore the amount ratio is everywhere larger than 1. However, Fig. 4a shows that this ratio strongly varies from close to 1 to more than 6. Comparison with the climatology in Fig. 2b shows that lower ratios are found in areas where annual precipitation is high, such as within the ITCZ (where annual precipitation exceeds, on average, 2500 mm; see Fig. 2b) and along the mid-latitude storm tracks (roughly between 30^{o} and 60^{o} latitude in both hemispheres, where averaged annual precipitation in Fig. 2b is of the order of 1500 mm). These low precipitation amount ratios are consistent with the high numbers of extreme seasons in these regions (Fig. 2a). In contrast, high ratios of precipitation amounts are observed in areas where annual amounts are low, such as near the poles and in the arid subtropical areas along 30^{o} latitude in both hemispheres. The latter areas are climatologically affected by the descending branch of the Hadley cell, typically inhibiting precipitation occurrence and, therefore, an anomalously high seasonal precipitation amount has the potential of exceeding climatological values by a large factor. Finally, Fig. 4a shows that areas characterized by extreme seasons with amount ratios between 2 and 4 are located between strongly contrasting regions in terms of annual precipitation amounts (Fig. 2b). It is in these regions where spatial anomalies in the occurrence of precipitating weather systems (e.g., due to anomalous cyclone tracks) may play a crucial role in forming extreme seasons. This will be discussed in more detail in section 6.

To gain more statistical insight into the factors that lead to extreme seasons, Figs. 4b and 4c show the ~~number of~~ ratios of extreme daily precipitation events and wet days in extreme seasons with respect to climatology (evaluated for the same 90-day periods as the extreme seasons but in all 40 years). Daily extremes are defined individually at each grid point as daily precipitation values exceeding the 98th percentile of all wet days in the 40-year dataset, while wet days are defined by daily accumulations that exceed 1 mm. Comparing Figs. 4b and 4c, it ~~is obvious~~appears that the ratios of daily precipitation extremes and wet days ~~seem to~~ show a contrasting pattern: a high ratio of daily precipitation extremes tends to co-occur with a low ratio of wet days, and vice versa. This is especially evident in areas that ~~present~~feature particularly large and small ~~high and low~~ ~~of contrasting~~ precipitation amount~~s ratios in Fig. 4a~~. For instance, in the ITCZ where precipitation is climatologically very frequent, an extreme season may~~ only~~ occur due to increased rainfall amounts. This is reflected in the anomalously high ratios of daily precipitation extremes in extreme seasons (Fig. 4b). In contrast, in arid areas where rainfall occurs rarely (outlined by dashed contours in all panels of Fig. 4), a small increase in the number of wet days ~~than climatologically~~ can be responsible for a dramatic increase of seasonally accumulated precipitation. It is thus plausible that the lower the climatological precipitation amounts in an area, the more an extreme season is characterized by an anomalously high frequency of wet days. On the other hand, in climatologically wet regions (such as in the tropics, within the solid contours of Fig. 4), extreme seasons are related to an anomalously high frequency of daily extremes. Apart from this contrast between climatologically wet and dry areas on the globe, some regions have relatively high ratios of both daily extremes and wet days. Indeed, when comparing Figs. 4b and 4c, areas with a high ratio of daily extremes are spatially less constrained than areas with a high wet-day ratio. This is especially true in the tropics and mid-latitudes (up to 60° of latitude), suggesting that daily precipitation extremes may play a more widespread role for the occurrence of extreme wet seasons than the number of wet days.

In both Figs. 4b and 4c, a large majority of ratios exceed the value of 1, suggesting that an extreme season typically occurs if there is a combination of both more wet days and more extreme events compared to the seasonal climatology. Indeed, Fig. 5a shows the probability density functions of the ratios of daily precipitation extremes and of wet days for all extreme seasons at all grid points. Clearly the spread of ratios of daily extremes is larger than the spread of ratios of wet days, with values between 1 and 5 and a median of 2.3 for daily extremes and a much narrower distribution with a median of 1.3 for wet days. Interestingly, the distribution for the daily extremes is bimodal with peaks near values of 1 and 2, respectively, where the first peak is related to arid areas. To combine information provided by the two ratios (mean values shown in Figs. 4b and 4c) and their variability (shown in Fig. 5a), we subjectively defined three ranges for the two distributions in Fig. 5a. These ranges are delimited by the peaks and the 75th percentile of the distributions (depicted by dashed lines in Fig. 5a). This forms a total of nine bins that serve to characterize each grid point according to the ratios of daily extremes and wet days required to form an extreme season (Fig. 5b). For instance, equatorial Africa and the Sahara are two contrasting regions of frequent and scarce precipitation, respectively. Cyan and light green colors in equatorial Africa indicate~~s~~ a low wet day ratio of less than 1.2 and a~~n intermediate~~ daily extreme ratio ~~between 2 and 3~~of more than 2. Therefore, in this region, an extreme season requires only slightly more wet days than in the climatology but at least 2 ~~to 3~~ times more daily extremes. ~~It is finally~~Before further discussing these patterns, it is noteworthy that 13% of all grid points feature ratios of daily precipitation extremes below 1 (Fig. 5a). These values are concentrated in areas of scarce precipitation and are depicted by grey colors in Fig. 4b. For wet days ~~in Fig. 4c~~, ratios below 1 are even less common, they occur only for 3% of all grid points and typically exhibit values between 0.9 and 1 (Fig. 5a). In contrast to daily precipitation extremes, these grid points are scattered across areas of frequent precipitation (e.g. ITCZ and storm tracks), where wet day ratios are close to 1, i.e.~~,~~ where extreme seasons occur ~~in seasons~~ with roughly the climatological value of wet days.

Despite the high spatial variability in Fig. 5b, several regional patterns can be distinguished. Areas related to high precipitation amounts (Fig. 2b) and a large number of extreme seasons (Fig. 2a), such as the storm tracks, are depicted by ~~red~~yellow colors in Fig. 5b (e.g. along 60°S). These areas are characterized by wet day ratios of less than 1.2 and daily extreme ratios of less than 2. As discussed before, the identification of a high number of extreme seasons makes it difficult for these seasons to strongly exceed climatology. Other regions that experience high precipitation amounts due to the ITCZ have a daily extreme ratio exceeding 3 and a low wet day ratio of less than 1.2 (cyan color), in agreement with the previous discussion of extreme seasons in this region. Extreme seasons with high wet day and daily extreme ratios (purple colors) mostly occur in the transition between areas of high and low climatological amounts of precipitation (Fig. 2b), for instance in subtropical maritime areas in both hemispheres (e.g. the eastern Atlantic and Pacific Oceans), but also in the eastern tropical Pacific. Especially the latter experiences major El Niño–Southern Oscillation (ENSO) events, which lead to a strong increase of wet days and daily extremes. Continental regions in the mid-latitudes are mostly characterized by dark green and orange colors, suggesting that extreme seasons are characterized by 1.2~~0~~ to 1.6~~0%~~ more wet days and less than three times more daily extremes than in the climatology. It is however noteworthy that several coastal areas have extreme seasons characterized by the highest ratios of wet days and daily extremes (purple colors), as for instance Portugal, e~~E~~astern Australia, and Greenland.

4. Portrayal of extreme wet season patches

4.1 The 100 largest patches

The methodology to build patches of grid points with coherent extreme seasons (see Section 2.2) has been applied to all primary and secondary extreme seasons. Figure 6 shows the 100 largest patches in three panels to avoid overlapping. In these panels, patches are labelled by the month and year of the average date of all 90-day periods that compose the patches. The size of the patches in Fig. 6 varies between 1.7~~.~~5x10^{6}~~^{5}~~ km^2 and 1.86x10^{7}~~^{5}~~ km^2. The largest one occurred from January to March 1983 in the eastern tropical Pacific (Fig. 6a).

Several patches correspond to or include well-documented periods of anomalously high precipitation, and some of them also reflect singular weather events that produced enough precipitation to characterize a whole 90-day period as an extreme season. For instance, the patches in the western North Atlantic in Figs. 6a and 6c correspond to the anomalously active hurricane seasons of 2010 and 2017. In contrast to these active hurricane seasons, the patch in the same region in September 1988 (Fig. 6b) does not correspond to one of the most active hurricane seasons, but rather corresponds to the extremely intense Hurricane Gilbert (1988), one of the deepest hurricanes ever documented with a central pressure of 888 hPa. Other patches in the tropics agree with major ~~El Nino and La Nina~~El Niño and La Niña phases, such as the ones in 1982/1983, 1997/1998 and 2015/2016 in the central Pacific (Figs. 6a, 6b and 6c), and with ENSO-related extreme wet seasons in austral summer 2010/2011 (Fig. 6c; Ratna et al., 2014).

Within the storm tracks of the Northern Hemisphere, Fig. 6b shows two patches that are associated with anomalous variability of the polar jet: the first one corresponds to the extremely wet winter in the UK in 2013/2014, when an anomalously strong and persistent jet stream led to a series of extratropical cyclones hitting the region (Davies, 2015;

McCarthy and Spillane, 2016). The second patch in the central North Atlantic along 35°N in winter 2009/2010 is associated with an anomalous southward deviation of the North Atlantic jet that led to a high frequency of TMEs and enhanced precipitation over the western Mediterranean (Harnik et al., 2014; Sprenger et al., 2017). Other patches that depict known cases affected north-western Australia in 2000 and 2011 (Figs. 6a and 6c), associated with enhanced cyclone activity and a strong Mascarene high (Feng et al., 2013). Another example is discernible in the eastern Antarctic where anomalously high precipitation occurred in autumn 1980 (Fig. 6a) as discussed by Van Ommen and Morgan (2010). All these examples provide insight into the variability of the specific weather systems and/or climatological features that can lead to extreme wet seasons. This relationship will be analyzed more systematically in the following sections.

4.2 Four example patches and definition of their core period

The patches provide a spatial dimension to the identified extreme seasons. Before we can attribute the occurrence of weather systems to individual extreme season patches, we have to reconsider the temporal dimension of the identified patches. Because of However, our with our approach to build patches (see section 2.2) and especially, for might cause patches with many grid points, mighttothe extend their combined period of extreme seasons (identified at every grid point) can extend over a significantly longer period than 90 days. Such patches tend to be located in regions where many secondary extreme seasons were identified, such as in the Southern Ocean. This is plausibly due to a higher likelihood ofnumerous secondary extreme season periods at neighboring grid points whichthat canto fulfil the temporal overlap criterion of 68 days (section 2.2). in regions where there are more extreme seasons. In order to make the attribution to weather systems comparable across patches, the aim is here to define for each patch a "core period" that contains most of the area-integrated precipitation.

To illustrate this approach, we show detailed information about four selected example patches (labelled as a-d in Fig. 6) in Fig. 7. The central date, latitude and longitude of these patches are shown at the bottom of each panel. Figure 7a provides information about an elongated, tongue-like-shaped patch that affected the US west coast in winter 1992/93 (label a in Fig. 6a). Figure 7b corresponds to a rather large patch that covers parts of Australia in summer 2010/11 (label b in Fig. 6c). Figure 7c is for a patch in the Arctic in late summer 2016 (label c in Fig. 6a), and Fig. 7d presents an example in the Asian summer monsoon region in 1991 (label d in Fig. 6b). The time period in each panel of Fig. 7 spans the earliest day (referred to as day 1) and the latest day (e.g. day 200 in panel a) from all 90-day extreme season periods that contribute to the considered patch. For each patch, three time series are shown in the panels of Fig. 7: (i) the upper graphs show time series of daily precipitation summed over all grid points that include the same day within their corresponding 90-day extreme seasons.; For instance, let a certain day in the abscissa to be included in the 90-day extreme seasons of 15 out of 30 grid points that compose a patch. Then the upper graph of Fig. 7 shows the sum of daily precipitation in these 15 grid points for that certain date. (ii) The middle graphs shows what we call the "percentage of contributing grid points", i.e. the percentage of grid points of the patch that contain the considered day in their 90-day extreme season period; and (iii) the bottom graphs indicate the occurrence of weather systems, as discussed below. For instance, the patch in the western US has a peak of area-integrated precipitation of ~23x10^{12} liters on day 52. This value corresponds to the sum of daily precipitation from all grid points of the patch (the percentage of contributing grid points is 100%), i.e. this day is included in all 90-day extreme season periods of the grid points that compose this patch.

This visualization is now helpful to explain how a "core period" can be determined for each patch. All four examples show that at the beginning and near the end of a patch period, only few grid points contribute to the patch and the area-integrated precipitation values are lower in these periods. Also, in all cases, there is a more or less central time interval when (almost) all grid points contribute to the patch, and in these intervals the integrated precipitation is largest. We therefore define the core period as the longest period during which at least 25% of the respective grid points contribute to the patch. Considering again the western US patch (Fig. 7a), the so-defined core period extends from day 8 to day 104; for the monsoon patch (Fig. 7d) it becomes much longer from day 6 to day 141. ~~Therefore, c~~It is noteworthy that core periods may not include days with locally intense precipitation events that don't affect a large fraction of the patch area. The intention of the core period is to consider precipitation in the entire larger-scale area of the extreme season patch, and to identify the time period that is most important for precipitation in the patch as a whole. Core periods of patches may last longer than 90 days, i.e. the default time period that was initially used to define extreme seasons at individual grid points. In fact, further analysis shows that for all 3734 patches, the median and the 75th and 95th percentile values of the core period durations amount to 99, 114 and 147 days, respectively. Assigning a flexible core period duration to each patch allows extreme wet season patches to take into account the climatological characteristics of the different regions on the globe. For instance, core periods in the tropics (Fig. 7d) may last for more than 100 days, corresponding to the duration of an intense monsoon season.

Finally, we now investigate the occurrence of the four objectively identified weather systems (Table 1) during the core periods of the four example patches. The bottom graphs in the panels of Fig. 7 show colored lines for each weather system type indicating the days when a system overlaps with parts of the patch. Three shadings of colors are used to indicate whether 5 to 33% of the grid points of the patch overlap with the weather system (light shading), or whether this percentage amounts to 33–66% (medium shading), or to more than 66% (dark shading). For instance, dark green bars in Fig. 7a denote days when TMEs overlap with more than 66% of the western US patch. ~~(especially~~ WCBs never exceed 33% in Fig. 7 and thus only light blue shading is visible~~)~~. This provides qualitative information about the occurrence and relevance of a weather system to the precipitation in the patch. Indeed, all four identified weather systems are known to be climatologically highly relevant for heavy rainfall. It is however noteworthy that large patches may exhibit several local maxima of precipitation on a given day, but not all of them necessarily overlap with one of the weather systems. In the following, we further investigate the ~~four~~ exemplary patches of Figs. ~~-~~ 7a, 7b and 7c to better understand the contribution of the four weather systems to the precipitation in these extreme season patches.

5. Examples of how weather systems contribute to extreme wet seasons

5.1 Cold season patches in the subtropical-mid-latitude transition zone

The timeseries for the subtropical-to-mid-latitude patch in Fig. 7a exhibits distinct peaks in the 96-day core period. Several of these peaks coincide with cyclones and TMEs, as shown in the bottom graph by the red and green lines, respectively. Figure 8 provides insight into the complex relationship between precipitation, cyclones and TMEs for this patch, but also for another patch of similar latitudinal extent and orientation that affected the Iberian Peninsula in late autumn 1989 (note that this additional patch is not depicted in Fig. 7). ~~(not shown in Figs 6 and 7).~~~~This additional case is not shown in Figs. 6 and 7 but it is mentioned here to provide insights into the frequency and areal extent affected by weather systems that produce extreme seasons.~~ ~~For both cases,~~ Figures~~.~~ 8a and 8b show that the patches present core period precipitation amounts that exceed climatological values by a factor that varies from 2 to 5.~~' core periods are related to precipitation amounts of about 2 to 5 more than in climatology.~~ ~~show accumulated precipitation during the extreme season core periods of 200 to 550 mm with several local maxima. Local maxima in the northern parts of the patches correspond to regions where cyclones occurred frequently (10 to 20% of the core period).~~ ~~Especially~~ In fact, the northern parts of the patches are ~~affected by a~~ related to positive anomalies~~y~~ of cyclone~~s~~ occurrence of ~~the order of~~ 5 to 15%. On the other hand, the southern parts of both patches are co-located with climatological anomalies~~ous~~ of northern extensions of TME occurrences ~~of~~~~the northern extension of frequent TMEs~~ of the same order as for cyclones ~~occurrences (~20% of the core period)~~. It thus seems that cyclones act in synergy with TMEs to produce the large amounts of precipitation within the patch~~are the main contributors of precipitation to the patches, enhanced by the high availability of water vapor due to TMEs~~. Blue lines in the lower graph of Fig. 7a coincide with prominent peaks of area-integrated precipitation in the US patch, for instance on day 40. Hence, despite their rather ~~non-~~infrequent occurrence, WCBs may ~~significantly contribute~~still constitute a key dynamical ingredient to extreme ~~to~~ seasonal precipitation amounts. To underline this point, Figs. 8c and 8d show daily precipitation, sea level pressure, and the spatial extent of TMEs and of ascending WCBs for peak precipitation days during the US patch (day 40, i.e. 29 December 1992) and the Iberian patch (26 December 1989), respectively. In both cases, the local maxima of daily precipitation exceeding 50 mm coincide with WCBs in the warm sectors of deep cyclones. Such amounts represent large contributions to the total precipitation during the patches' core period and thus the two examples suggest~~sugest~~ links between processes on the weather timescale (extratropical cyclones and their associated WCBs) and seasonal-scale extreme precipitation. In fact, both these extreme wet season patches are in areas where cyclones and WCBs contribute frequently to intense precipitation (Pfahl et al., 2014; their figure 8). ~~Finally, most cyclones co-occur with RWB events (Fig. 7a). However, this comes as no surprise since subtropical cyclones are typically instigated by the equatorward extensions of upper-level stratospheric filaments.~~

5.2 Warm season patch in the tropical-subtropical transition zone

Figure 9a provides more information about the northern Australian patch in summer 2010/11, previously introduced in Fig. 7b. This patch covers large parts of the maritime areas northwest of Australia and includes a tongue-like extension to the center of the continent. Large parts of the patch overlap with areas with high cyclone frequencies, especially close to the west coast at 115ºE, 20ºS. In this part of the patch, a ~~highthe anomaly of~~positive cyclone~~s occurrence~~ frequency anomaly ~~is high and my exceed~~of 10 to 20%~~, producing 5 times more~~ is collocated with seasonal precipitation amounts of more than 5 times the climatological value~~an in climatology~~. On the other hand, ~~However,~~ the northern part of the patch is located within the ITCZ ~~during~~ of the Australian summer,~~. In this region,~~ ~~in~~ a region where Coriolis forces are too weak ~~for~~ to favor cyclogenesis~~nes to develop. However,~~. However, Fig. 9a shows that RWB events~~occur~~ along the northern part of the patch took place during its core period with an anomalous occurrence of 20% with respect to climatology. ~~during 60% of the patch's core period. Such upper-tropospheric systems~~~~The upper-level PV streamers resulting from t~~These~~he~~ RWB events can significantly contribute to the formation of precipitation by reducing the static stability beneath and forcing vertical ascent.

Further analysis showed that the narrow continental tongue of the patch is associated with a specific event: the landfall of tropical cyclone Yasi (track is shown in Fig. 9b). Yasi made landfall at the Australian east coast and moved into the continent in February 2011, contributing strongly to the precipitation peak around day 165 in Fig. 7b. Consequently, this Australian patch has been formed through the combined contribution of climatological features (the ITCZ), enhanced precipitation by RWB, but also due to the frequent occurrence of cyclones in the northwest of Australia plus the single, prominent system of tropical cyclone Yasi. Therefore, ~~as illustrated in Fig. 9, patches should not necessarily be regarded as spatially coherent, because~~ the~~ir~~ spatial extension of extreme season patches can be due to a combination of specific weather systems that occur in different subregions of the patch~~such as tropical cyclones and climatological features such as the ITCZ~~.

5.3 The summer 2016 patch in the Arctic

Figure 7c depicts a large patch that covers the eastern Arctic in late summer 2016 (dotted area in Fig. 10). Figure 10 shows that a large part of this patch is related to an anomalous occurrence of cyclones of 5 to 10% with respect to climatology.~~,~~ ~~with frequencies more than 25% higher than in the climatology.~~ The region with anomalously frequent cyclones (red contour) agrees with the southward extension of the patch into Siberia near 150ºE and with an anomalously high precipitation excess compared to climatology~~ of more than~~, with a ratio of more than 1.7. Figure 7c shows that several prominent peaks in the precipitation time series coincide with WCBs and RWB events, similarly to the subtropical patch in Fig. 7a. The year 2016 has been recorded as the warmest in the last decades in the Arctic and was characterized by anomalously low sea-ice extent and overall positive sea surface temperature anomalies that enhanced evaporation and consequently precipitation (Simpkins 2017; Overland et al., 2018; Petty, 2018). ~~Such conditions led to the extreme season in the eastern Arctic and probably reflect a rainier future regime in the Arctic region (Bintanja, 2017).~~ Evidently, such conditions can lead to extreme wet seasons in the eastern Arctic and are similar to the ones leading to a rainier future regime in the Arctic region (Bintanja, 2017).

~~**5.4 Patch in the Asian monsoon region**~~

~~**The tropical patch in Fig. 7d covers large part of the Bay of Bengal and affects Southeast Asia (Fig. 11). Indeed, Fig. 11 shows a local maximum of accumulated precipitation over Myanmar of about 2700 mm. The rather long core period of this patch reflects the intense monsoon season in the region from June to mid-October. High values of area-integrated precipitation occur during the whole core period (Fig. 7d). In contrast to the other examples, few cyclones and TMEs overlap with the patch. In contrast, RWB events are frequently present mainly on the eastern side of the monsoon anticyclone (Kunz et al., 2015; their Fig. 9a). Figure 11a shows that there is indeed a high percentage of identified RWB during the core period, mainly at the eastern side of the patch, within the latitude range of 5° to 20°N. An example of a prominent RWB event is presented in Fig. 11b, which shows a tongue of high PV values (>1.5 PVU) extending from China into the Bay of Bengal at 10°N. This streamer is co-located with several local maxima of daily precipitation within the patch, plausibly contributing to the occurrence of daily extreme events, a necessary aspect of extreme wet seasons in this region (Fig. 5b).**~~

6. The contribution of weather systems to extreme wet seasons: a global view

Following the ~~four~~three examples of the previous section, we quantified the occurrence of the four objectively identified weather systems during all the 3734 identified patches. To this end, we counted the number of days with an overlap of each weather system with the patch during its core period. In order to then estimate whether these numbers are anomalous compared to climatology, this process was repeated for the same dates and grid points as for the core period, but for all 40 years of our dataset. The ratio then defines the overlapping frequency ratio of a patch with respect to climatology and results are presented in Fig. 11~~2~~. For instance, orange patches in Fig. 11~~2~~a are overlapping about 2.5 times more often with cyclones during their core periods than in the climatology. In addition~~ to all patches~~, the right-hand panels of Fig. 11~~2~~ show the latitudinal distribution of the overlapping frequency ratios. They were calculated by zonally averaging the ratios of all patches within +/- 7.5° of each latitude degree. Figure 11 provides a global view of the relationship between patches and the occurrence of the identified weather systems. To provide a seasonal perspective of Fig. 11, but also to increase the figure clarity, we include in the supplementary material four versions of Figure 11, each showing only patches with a central date of their core period in boreal winter (DJF), spring (MAM), summer (JJA), and autumn (SON).

Figure 11~~2~~a reveals the importance of cyclones for the formation of precipitation in extreme wet seasons. ~~The largest part of the world~~Most latitudes except in the tropics ~~is~~are covered by patches with frequency ratios of at least 1.2. The latitudinal distribution of these ratios shows two local maxima in the subtropics close to 30° latitude. The origin of these maxima ~~may~~cannot ~~not~~ be attributed clearly~~ attributed~~ to either tropical, subtropical or extratropical cyclones. Nevertheless, Fig. 3 shows that these regions experience their extreme seasons in the colder months of the year and thus it is rather unlikely that tropical cyclones may contribute to their formation. Indeed, Fig. 11~~2~~a shows that several patches in the subtropics have cyclone frequency ratios of more than 2, and in some cases even more than 4. Patches with high ratios occur in particular in subtropical oceanic regions, in transitional areas between climatologically high and low precipitation amounts (Fig. 2a). These regions are also characterized by an anomalously high number of wet days and daily extremes ~~in~~ (Fig. 5b). ~~In accordance with Pfahl and Wernli (2012), which implies that individual cyclone tracks that occur equatorward of the climatological storm tracks may produce daily precipitation extremes and thus significantly contribute to extreme seasons.~~This result suggests that cyclones occurring equatorward of the climatological storm tracks are a key ingredient for extreme wet seasons since they trigger anomalously frequent precipitation extremes in these regions [~~(~~see also Pfahl and Wernli (2012)]. Low ratios in Fig. 1~~12~~a occur along the equator due to the absence of cyclones, but also within the storm track regions (e.g. along 60°S). Especially in the Southern Hemisphere, the right panel of Fig. 1~~2~~1a shows that ratios decrease monotonically from 1.45 at 30°S, to 1.1 at 60°S. This result suggests that the closer a patch is located to a climatological storm track, the more unlikely it is for this patch to overlap with more cyclones than in the climatology. The same also holds in the Northern Hemisphere in the western North Atlantic and in the eastern North Pacific between 30 and 60°N.

~~WCBs are airstreams associated with extratropical cyclones that ascend along the cyclones' frontal surfaces. They are associated with both stratiform and convective precipitation, and they can contribute significantly to extreme precipitation events (e.g. Pfahl et al., 2014; Oertel et al., 2019). Since~~ WCBs are directly related to the occurrence of cyclones and can contribute significantly to extreme precipitation events (e.g. Pfahl et al., 2014; Oertel et al., 2019).~~,~~ Therefore, Figs. 1~~2~~1a and 1~~2~~1b are expected to be similar. This is partly confirmed by the latitudinal distribution of WCB ratios with peaks in the subtropics at 30°S and 25°N, similarly to the zonal averages of cyclone ratios. However, Figs. 11~~2~~a and 1~~2~~1b also present considerable differences. For instance, the frequency ratio of WCBs along 60°S (Fig. 11~~2~~b) is significantly higher than the one of cyclones (Fig. 11~~2~~a). This suggests that extreme seasons within the storm tracks are not formed due to a higher frequency of cyclones but due to ~~their physical characteristics. Indeed, a more frequent occurrence~~a higher frequency of WCBs. Indeed, WCBs contribute~~s~~ essentially to the enhancement of seasonal precipitation and thus to the formation of extreme seasons in mid-latitude oceanic regions, but also in continental and polar regions. However, it is noteworthy that the climatological infrequency of WCBs especially in the polar regions (e.g. Fig. 7c; see also ~~,~~Madonna et al., 2014a) can result in the high ratios in Fig. 11~~2~~b, even if few WCBs occurred during the extreme season.

TMEs correspond to the transport~~s~~ of moist air from the tropics ~~and extend~~ into the extratropics. ~~Therefore, TMEs are expected to favour high amounts of precipitation whenever they reach higher latitudes.~~Therefore, TMEs are expected to favor higher amounts of precipitation whenever they reach areas of strong ascending motion in higher latitudes. Indeed, Fig. 1~~2~~1c shows several patches with high TME frequency ratios, especially along 60°S, but also in the continental areas of Asia and North America. A quasi-constant zonal average of 1.1 is observed in the mid-latitudes (right panel of Fig. 1~~2~~1c), suggesting that TMEs may contribute to the formation of extreme seasons in the extratropics. However, this contribution is expected to be weaker than the one from cyclones and WCBs. ~~Occasionally, TMEs contribute to Arctic extreme seasons,~~

~~although as for WCBs, the high ratio values there results from very few events during the extreme seasons and even fewer in the climatology.~~Occasionally, TMEs contribute to the formation of extreme seasons in the Arctic, but the high ratios in this region (Fig. 11c) result from few events during the extreme seasons and even fewer in the climatology.

~~Finally, RWB events can directly favour regional precipitation through reducing the static stability of the atmosphere, or indirectly by inducing large-scale ascent and/or the formation of surface cyclones in mid- and polar latitudes (Wernli and Sprenger, 2007).~~ Finally, Fig~~ure~~. 11~~2~~d shows generally low values of overlapping ratios of RWB, rarely exceeding values of 1.5. This is a consequence of the fact that RWB is climatologically frequent and thus ~~the contribution of RWB to extreme wet seasons cannot be as significant as the one of cyclones and WCBs,~~the RWB frequency ratios cannot be as large as the ones of cyclones and WCBs, two weather systems with a lower climatological frequency. The latitudinal profile of RWB frequency ratios (right panel of Fig. 11~~2~~d) presents two local minima, both in the mid-latitudes of the two hemispheres where RWB is particularly frequent. However, when elongated RWB-related PV streamers~~stratospheric filaments~~ occasionally intrude into the tropics, then extreme precipitation may be triggered (Knippertz, 2007). Because such events are rare and intense, a maximum of RWB ratios occurs in the tropics. It is plausible that ~~RWB~~extensions of PV streamers into the tropics lead~~s~~ to daily extreme events, a necessary ingredient for the formation of extreme seasons in these latitudes ~~, as suggested by~~(e.g.~~;~~ Figs. 4b and 5b). ~~and discussed in Section 5.4. It is noteworthy that other than the four systems that we objectively identified in this study might be also involved in forming daily precipitation extremes in the tropics (e.g. a strongest ITCZ or warmer seas surface temperatures).~~Nevertheless, other weather systems or conditions than RWBs, cyclones and WCBs might be also involved in forming daily precipitation extremes in the tropics and thus be responsible for the formation of extreme seasons (e.g. a very strong ITCZ or warmer sea surface temperatures). ~~Finally, the relatively high frequency ratios in polar latitudes may be related to the high frequency ratios of WCB in polar latitudes (Fig. 12b), especially in the Southern Hemisphere.~~Finally, in polar latitudes there are relatively high frequency ratios of RWB that may be directly related to the high frequency ratios of WCBs in the same areas (Fig. 11b), especially in the Southern Hemisphere. Indeed, WCBs are known to ~~transport air masses of low PV towards the higher troposphere,~~ deepen the ridges in a poleward direction and thus to significantly contribute to RWB (e.g. Grams et al., 2011; Madonna et al. 2014b).

It is noteworthy that in all panels of Fig. 11 there are several patches where the ratios are below 1. This indicates that in the core periods of these patches fewer weather systems occurred than in the climatology. This can plausibly occur if the considered system is not decisive for extreme seasonal precipitation. In such a case, the frequency of occurrence in extreme seasons might be close to the climatological average, i.e. the ratio varies randomly around 1. For instance, the patch covering large part of the great Australian Bight, at the central-south side of Australia, has a ratio below 1 for TMEs (Fig. 11c) whereas cyclones and WCBs have relatively high ratios of 1.6 and 2.2. It is plausible that TMEs do not play a crucial role to the formation of this extreme season compared to other more important contributions from cyclones and WCBs. It is finally noteworthy that we adopted a phenomenological approach to assess the contribution of specific weather systems to the extreme seasons, which only considers the occurrence of a weather system (categorical yes or no) but not specifically its associated precipitation. As a result, it cannot be excluded that a specific weather system might strongly contribute to the formation of an extreme season, even if its seasonal occurrence frequency is lower than in the climatology.

7. Summary and conclusions

This study investigated extreme wet seasons globally, and introduced them as a new concept at the interface of weather and climate research. First, we defined primary extreme wet seasons separately at every grid point of ERAI as the 90-day period with the largest accumulated precipitation in the last 40 years. To also account for 90-day periods with only slightly less precipitation, we also considered periods that exhibit at least 90% of accumulated precipitation of the primary extreme season and called them secondary extreme seasons. Our results show that the definition of extreme wet seasons becomes a delicate issue in some areas. For instance, at some grid points in the Southern Hemisphere storm tracks up to 20 extreme seasons have been identified. In these regions where the variability is small compared to the mean, 90-day accumulated precipitation amounts show a rather small variability, rendering the label "extreme" for some of the identified seasons less meaningful from a statistical point of view. However, in many regions the identified extreme seasons exceed the climatologically expected precipitation amounts by large factors and several of them have been reported in the literature as particularly impactful.

Further analyses focused on the statistical characterization of extreme seasons by counting the number of wet days and daily precipitation extremes during the extreme seasons. The grand majority of extreme seasons include both more wet days and more daily extremes than in the climatology. Nevertheless, these two metrics allow different precipitation regimes to be delineated with two contrasting scenarios: regions of scarce precipitation (e.g. arid regions) where extreme seasons may only occur due to just a few more wet days, and regions with frequent precipitation (e.g. along the ITCZ) where daily extremes are pivotal for the occurrence of extreme seasons. Our results show that only extreme wet seasons in subtropical regions, i.e. located in the transition between rainy and arid areas, include significantly more wet days *and* daily extremes. A method was next applied to concatenate extreme seasons at individual grid points to patches, where each patch is affected by the same extreme season. Large patches were related to planetary-scale events such as extreme El Niño years, or the ITCZ, but also to single weather systems such as RWB and major extratropical cyclones and hurricanes making landfall in North America.

The importance of synoptic-scale dynamics for the formation of extreme seasons was also investigated by identifying four weather systems, known to be important for the (extreme) daily precipitation events, and by considering their overlapping frequency with the extreme season patches compared to climatology. To analyse and illustrate the complex interactionsFour weather systems, known to be related to (extreme) daily precipitation events, were used to understand the role of synoptic-scale dynamics in forming extreme wet seasons. These systems were objectively identified in the 40-year dataset in order to quantify their overlap with the extreme wet season patches. To illustrate the complex interactions between these four weather systems and extreme season patches, we first investigated in detail ~~four~~three example patches in the mid-latitudes, the (sub-)tropics, and, in the Arctic~~ and the tropics~~, respectively. Furthermore, we analyzed the global distribution of patches along with their relationship to the four objectively identified weather systems. Results highlighted the anomalously high occurrence of cyclones as a crucial element for the formation of most extreme seasons, except in the tropics and the storm tracks where cyclones are either unlikely to occur or very common. However, our results showed that extreme seasons in the storm track regions are related to an anomalously ~~high~~ frequent occurrence of ~~warm conveyor belt~~WCBs. Finally, ~~Rossby wave breaking~~RWB events have been found to contribute to the formation of extreme seasons at low latitudes, while ~~tropical moisture export~~TMEs were found to contribute to extreme seasons in the mid-latitudes and the sub-tropics. Consequently, weather systems of different latitudinal origin may be important for the formation of extreme seasons. In fact, our overall results showed that extreme wet seasons can be either related to a higher occurrence of similar weather systems (e.g. the hyperactive hurricane season of 2017), to the contribution of single exceptional events (e.g. the landfall of hurricane Yasi for the Australian extreme season in summer 2011), and/or due to the influence of weather systems that are climatologically uncommon in specific regions (e.g. RWB in the tropics).

The variability of atmospheric dynamics within a 90-day period is large and therefore it is a challenge to perform a detailed quantification of the contribution of weather systems to extreme wet seasons. Nevertheless, our results show that valuable conclusions can be reached by combining the objective identification of weather systems, together with a grid-point-based statistical analysis of precipitation. In this context, a high number of patches, especially the ones shown in Fig. 6, may be considered as interesting cases of highly anomalous seasonal precipitation that merit further investigation. Therefore, future research could focus on such case studies to better determine the degree of complexity of the dynamics involved, to develop new statistical characterizations of seasonal precipitation, or even bridge more efficiently climate and weather perspectives on extreme wet seasons.

Acknowledgements. The authors are thankful to the two anonymous Reviewers who helped us improve the quality of this paper with their constructive comments.

Data availability. ERA-Interim data can be downloaded from the ECMWF web page at: https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/ (European Centre for Medium-Range Weather Forecasts, 2020). The supplementary material provides the core periods and grid points of all patches used in our analysis.

Financial support. EF, MR and MB acknowledge~~s~~ funding of the INTEXseas project from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 787652).

Author contributions. EF and HW conceived the study and methods. EF wrote major part of the paper and performed the analysis. MS provided technical support and all co-authors contributed to writing the paper and commented on its earlier versions.

Competing interests. The authors declare that they have no conflict of interest.

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Tables

Cyclones	Grid points within the outermost sea level pressure contour enclosing one local minimum (Wernli and Schwierz, 2006)
Warm conveyor belts	Grid points overlapping with the ascending part (between 800 and 400 hPa) of air parcels that rise for at least 600 hPa within 48 hours (Madonna et al., 2014a).
Rossby wave breaking	Grid points were either PV cutoffs or streamers are located. PV cutoffs: Grid points with stratospheric air (PV > 2 PVU), detached from the main stratospheric body on any isentropic level between 305 and 370 K (Wernli and Sprenger, 2007). PV streamers: Grid points within narrow filaments of stratospheric air on any isentropic level between 305 and 370 K (Wernli and Sprenger, 2007).
Tropical moisture exports (TME)	Grid points overlapping with 7-day forward trajectories started from the tropics (20°S–20°N) that reach 35° latitude in either hemisphere with a horizontal moisture flux of more than 100 g kg^{-1} m s^{-1} (Knippertz and Wernli, 2010).

Table 1 Short description of the six objectively identified weather systems.

Figures

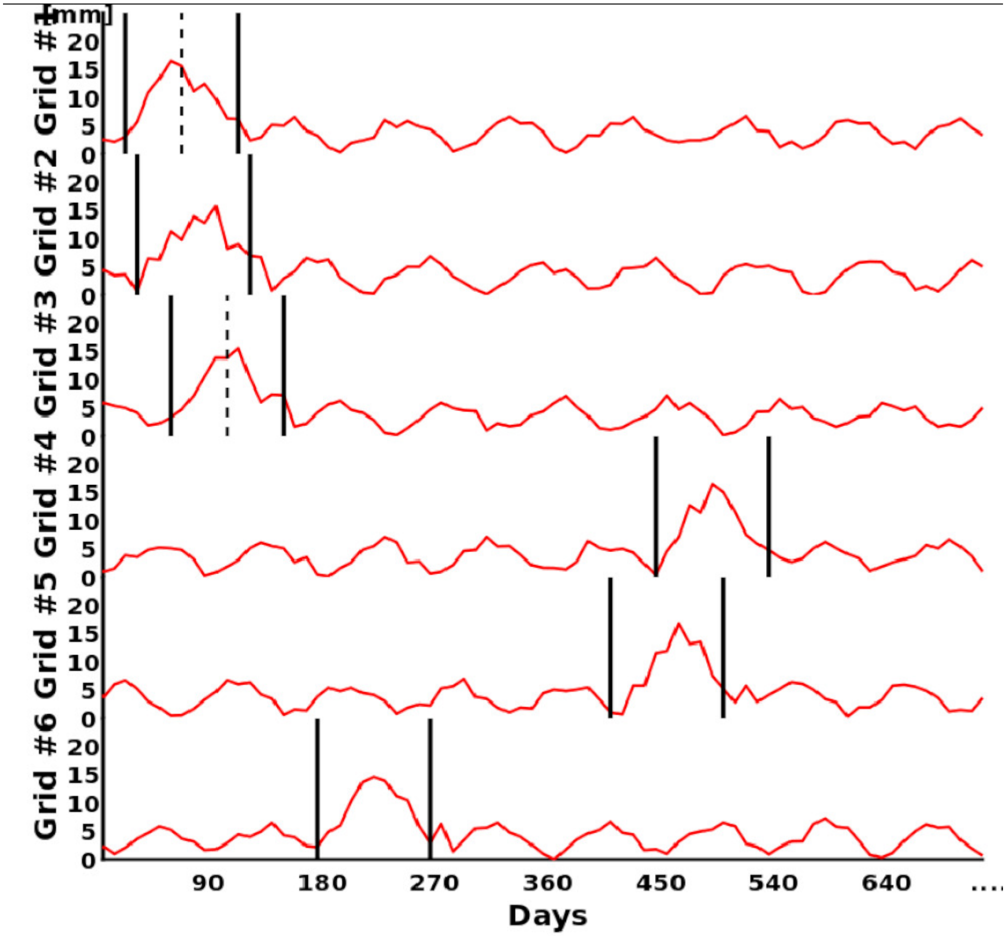


Figure 1 Methodological approach in an idealized one-dimensional grid to identify spatial coherences of extreme seasons. Red lines show precipitation time series per grid point, vertical black lines delineate the identified extreme season per grid point and vertical dotted lines depict their central date (only for two seasons, to be used as an example in text).

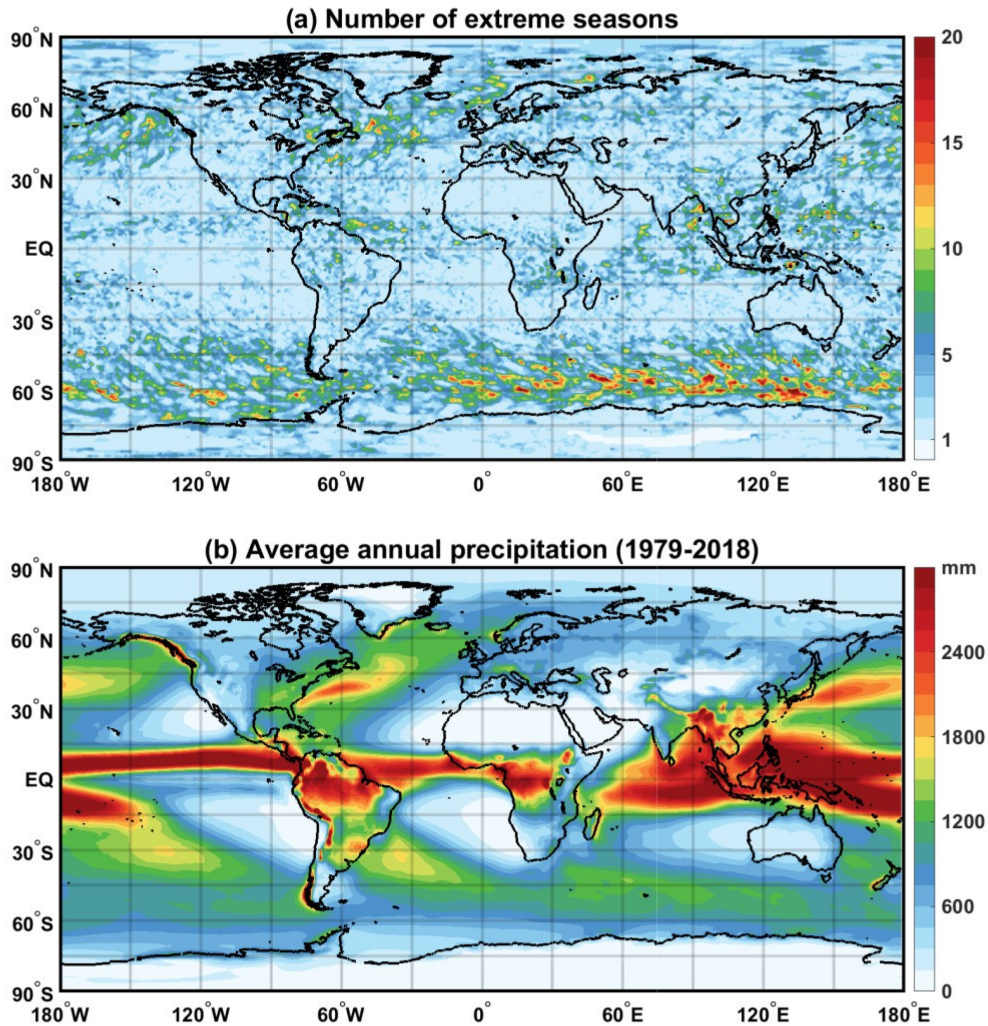


Figure 2 (a) Global distribution of the number of extreme seasons. **(b)** Average annual precipitation in a 40-year period (1979-2018).

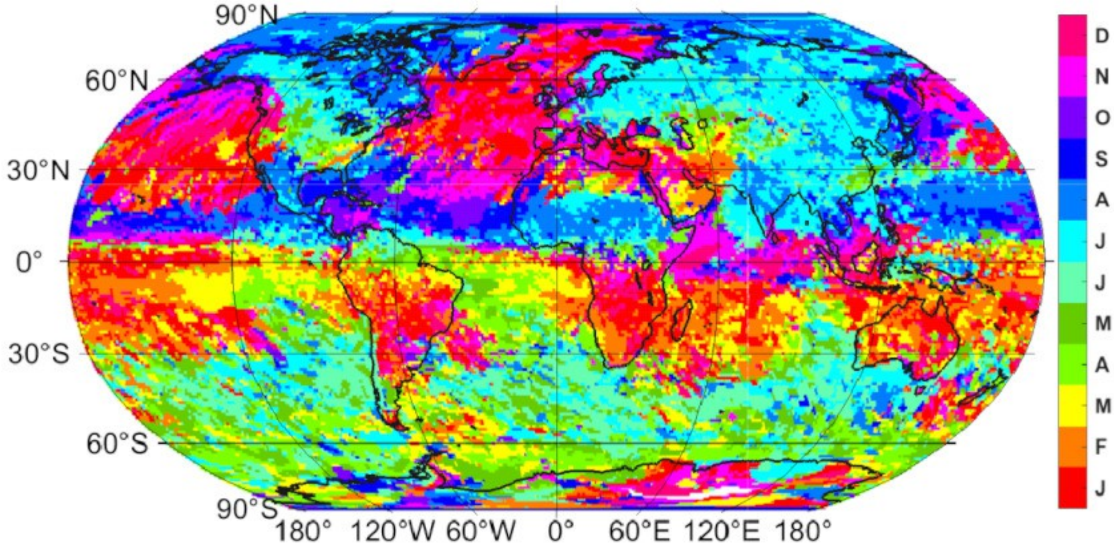


Figure 3 ~~Monthly distribution~~Month during which ~~of~~ the central day of the primary extreme season occurred at each grid point~~s~~.

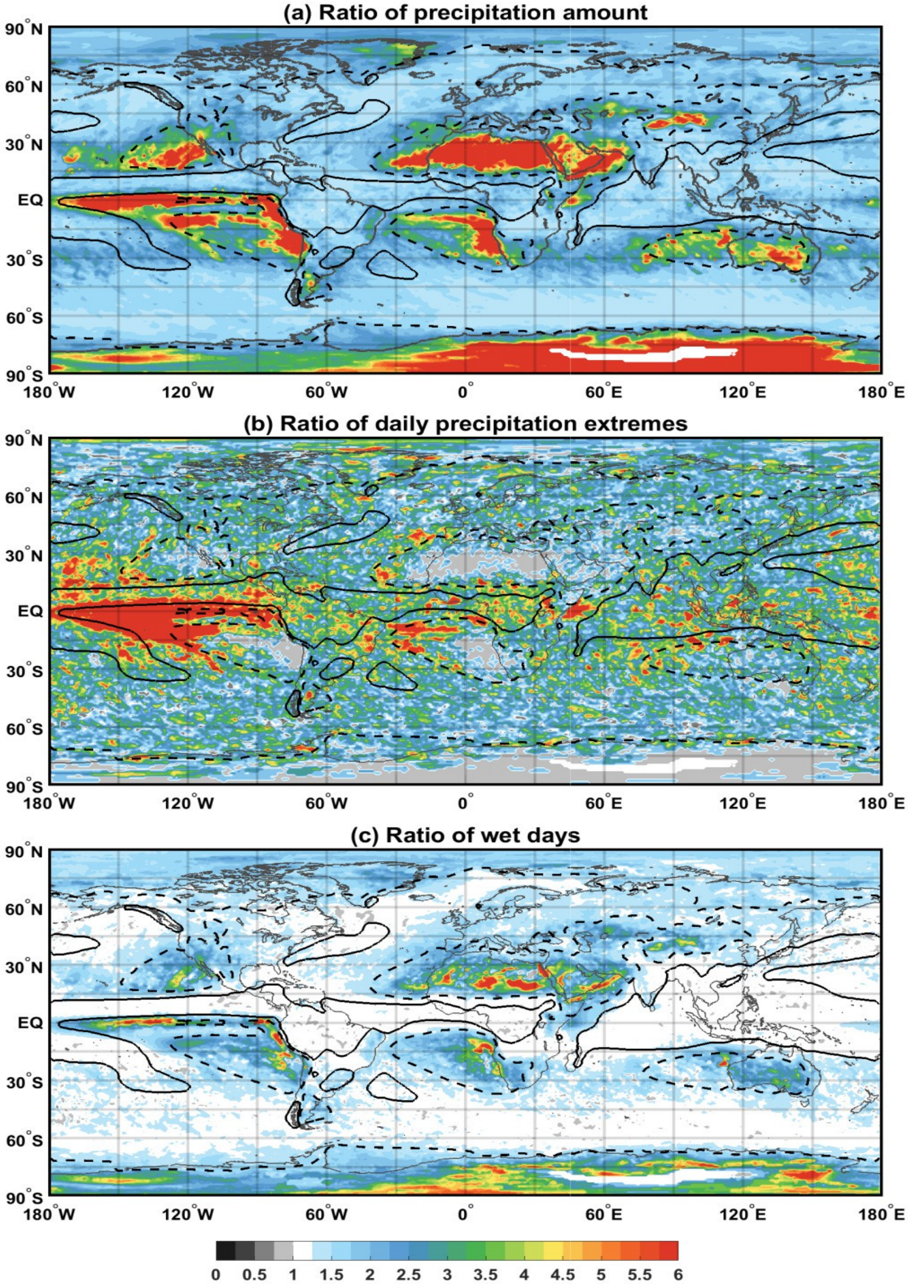
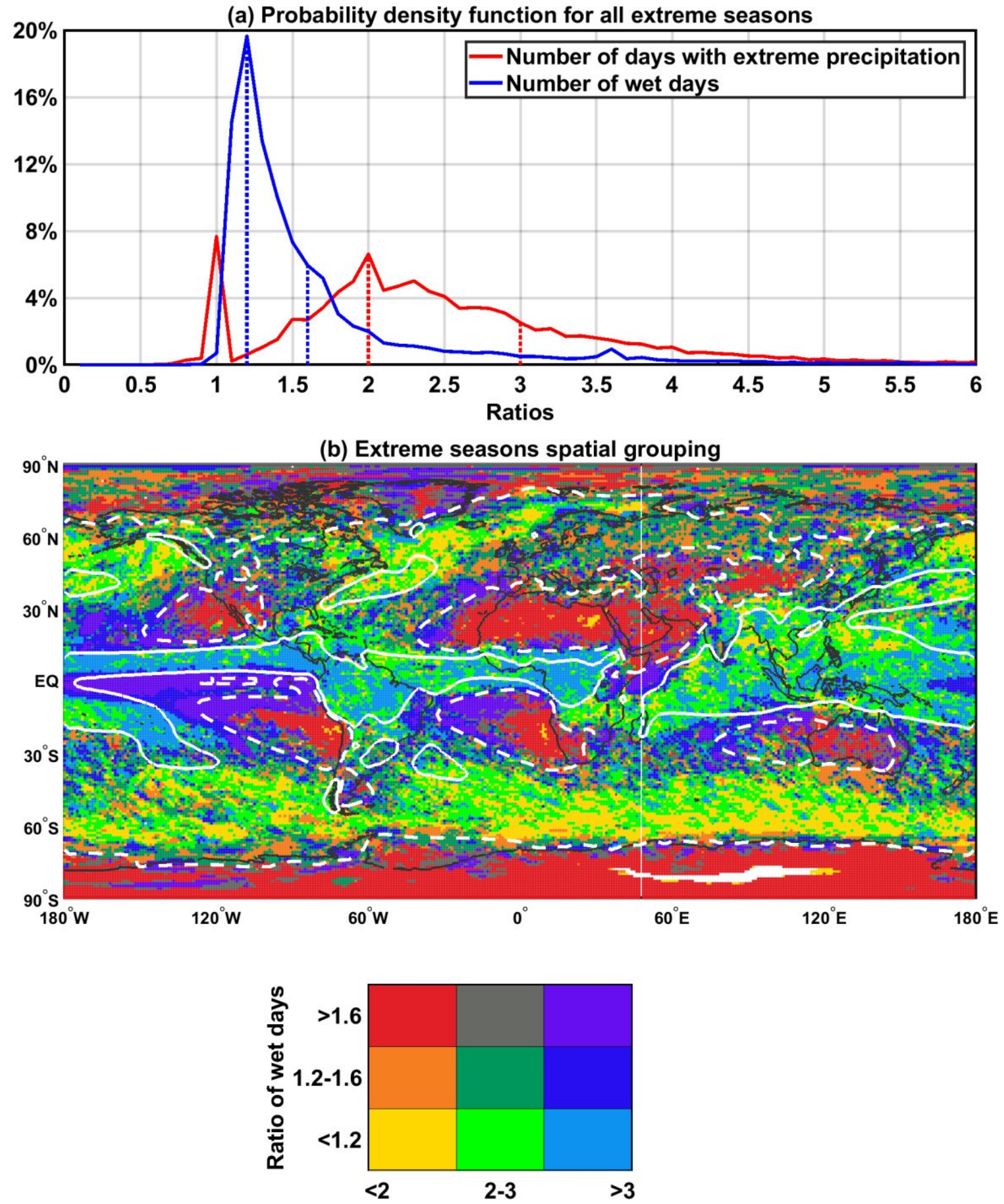


Figure 4 ~~**(a) Ratio of precipitation amount of extreme seasons respect to seasonal average and (b) the ratio of the number of daily precipitation extremes included in an extreme season respect to the seasonal average. (c) as in (b) but for the number of wet days.**~~ **(a)** Ratio of precipitation amount of extreme seasons with respect to the seasonal average, and **(b)** the ratio of the number of daily precipitation extremes included in an extreme season with respect to the seasonal average. **(c)** as **(b)** but for the number of wet days. Dashed and solid contours depict annual average precipitation of 500 and 1500 mm.



~~**Figure 5 (a)** Probability density function of number of ratios of daily precipitation extremes and wet days for all extreme seasons and for all grid points. Vertical dotted lines correspond to ratios of 1.2, 1.6, 2 and 3. **(b)** Attribution of grid points to combined climatological ratio fractions of number of wet days and daily precipitation extremes. Fractions are delimited by dotted lines in panel **a**.~~**Figure 5 (a)** Probability density function of the number of ratios of daily precipitation extremes and wet days for all extreme seasons and for all grid points (ratios with respect to the seasonal average). Vertical dotted lines correspond to ratios of 1.2, 1.6, 2 and 3. **(b)** Attribution of grid points to nine categories of pairs of ratios of the number of wet days and of daily precipitation extremes. Dashed and solid white contours depict annual average precipitation of 500 and 1500 mm, respectively. Dotted lines in **(a)** show the category boundaries used in **(b)**.

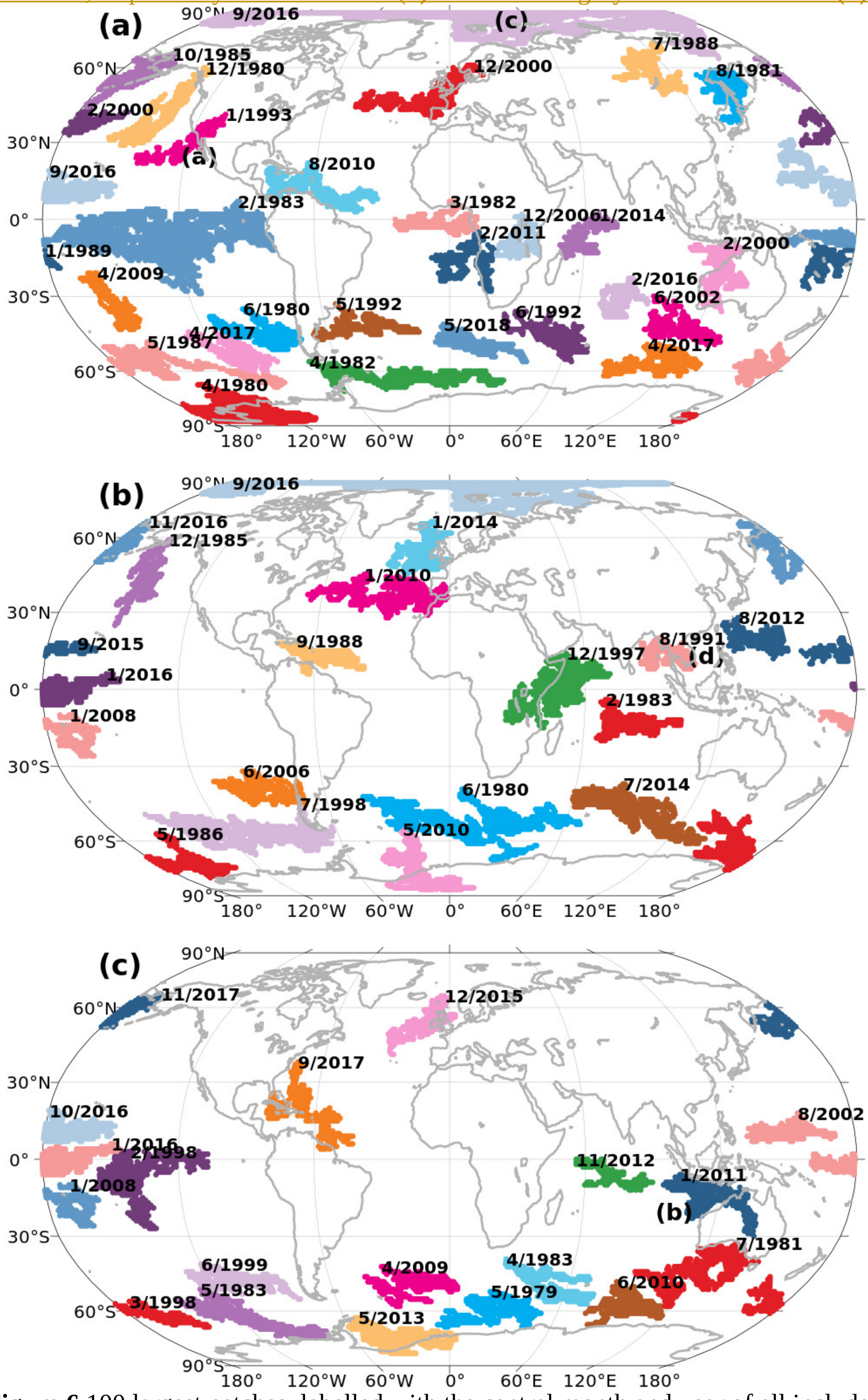


Figure 6 100 largest patches, labelled with the central month and year of all included extreme season. For clarity reasons, all areas are distributed in three panels and are depicted by different random colors. Four patches are also labelled by a green letter that corresponds to panels in Fig. 7.

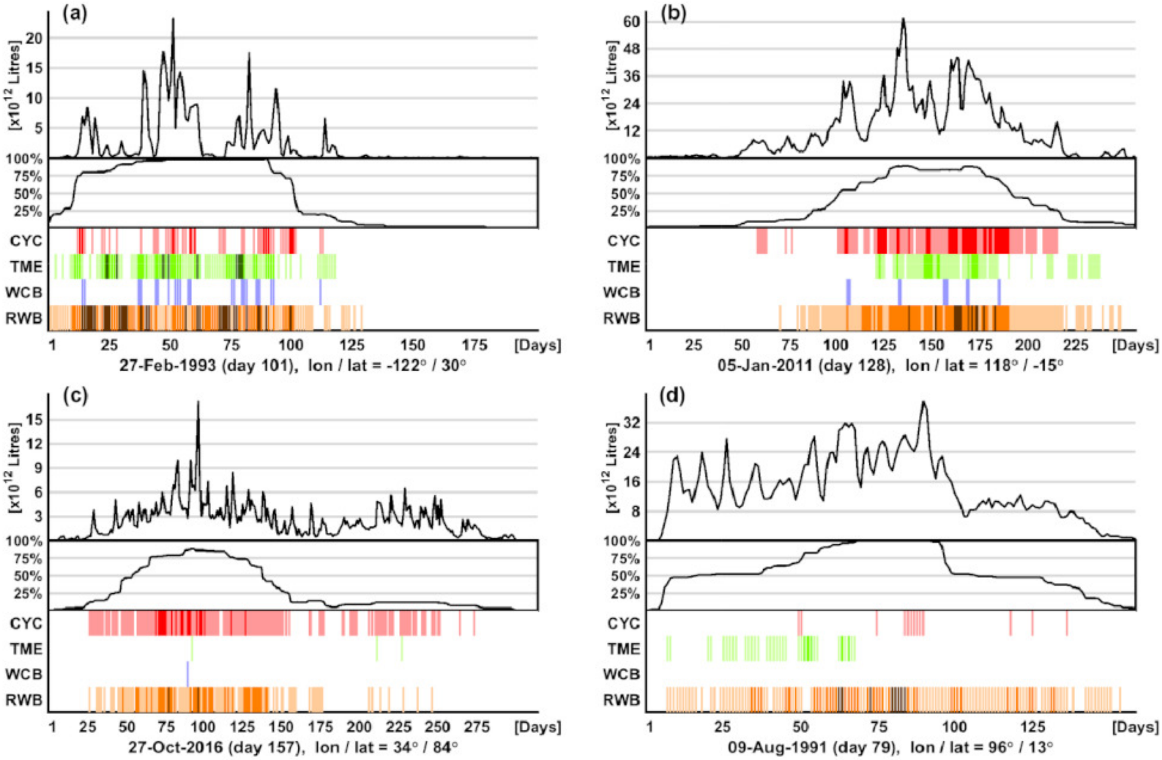
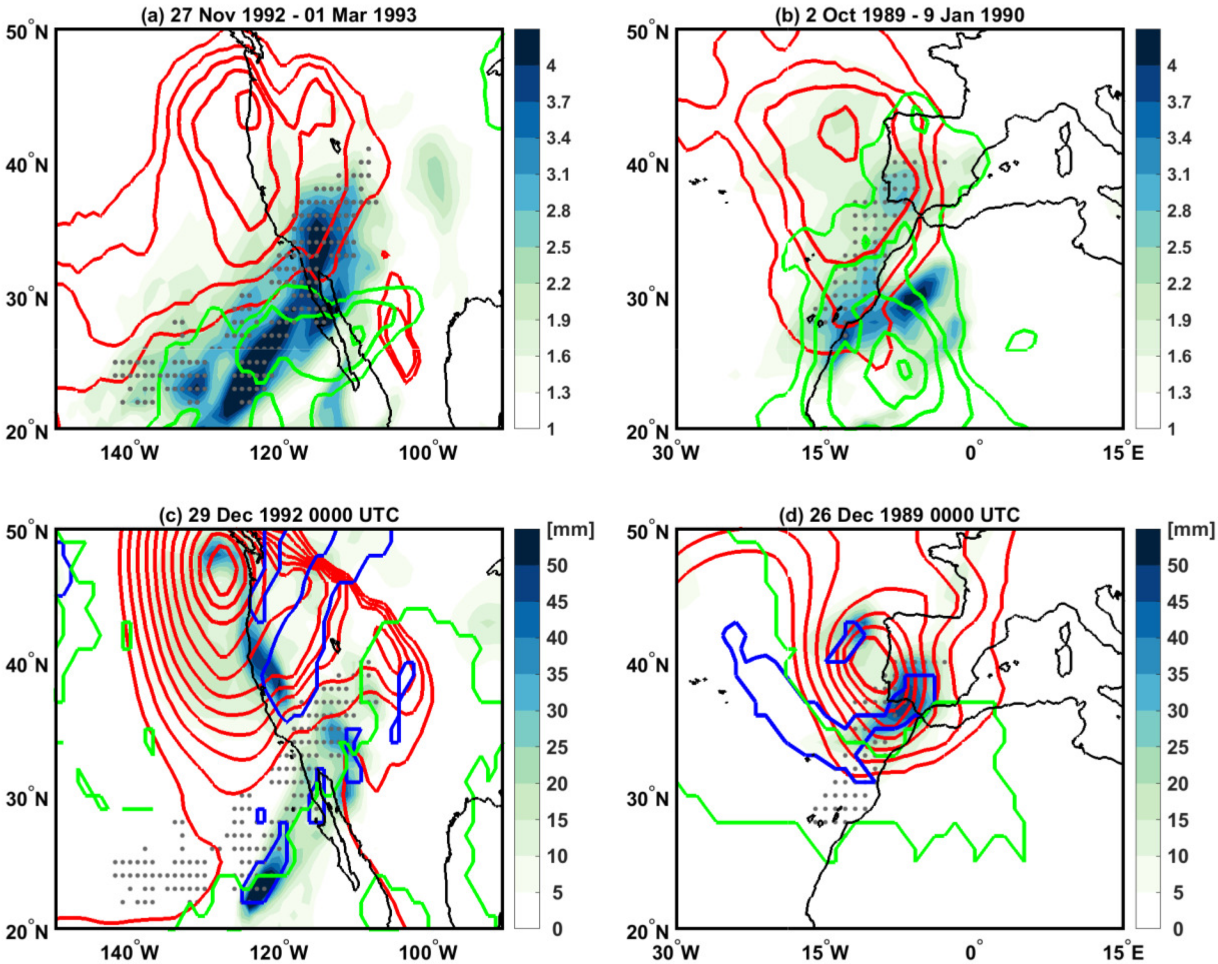
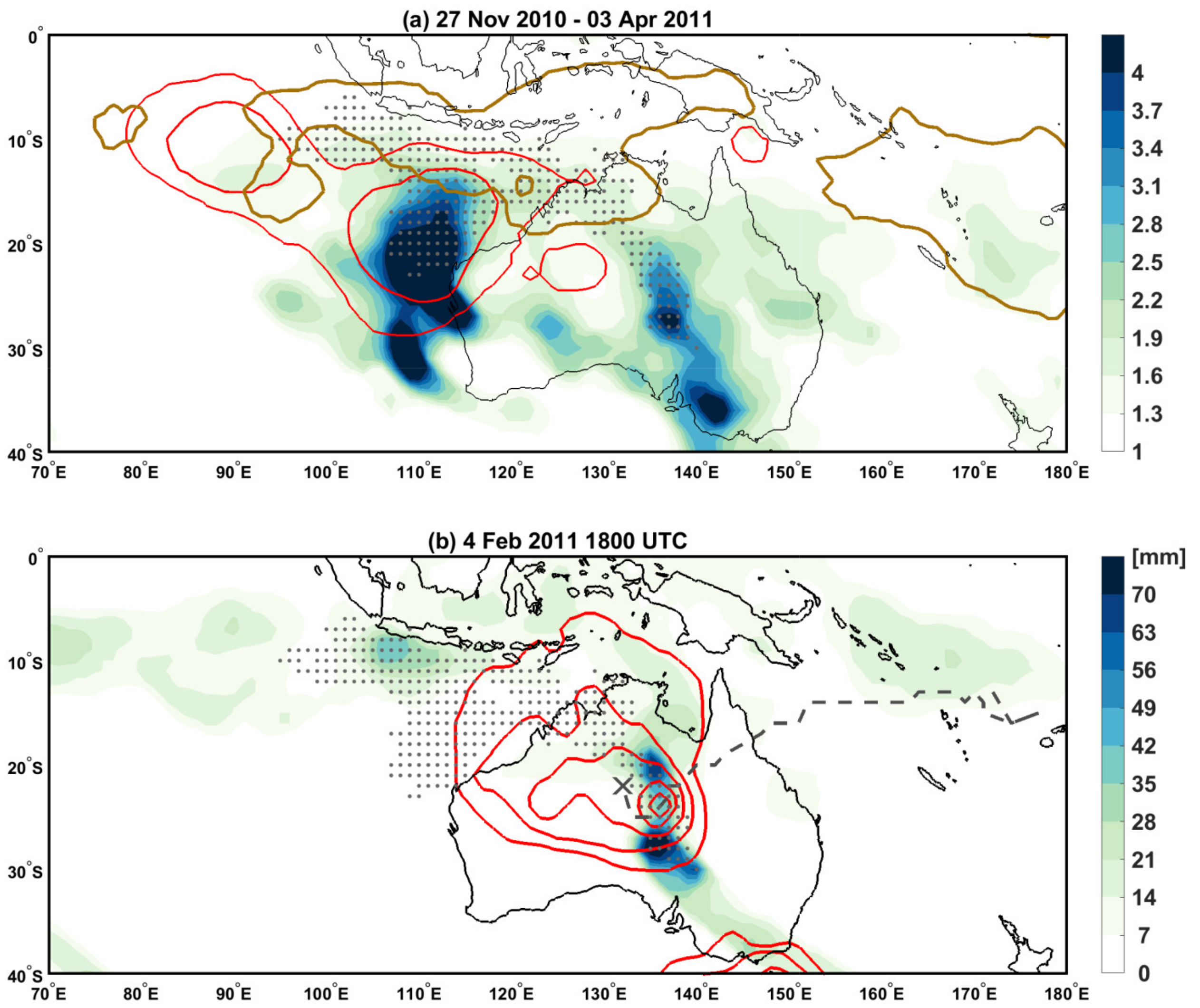


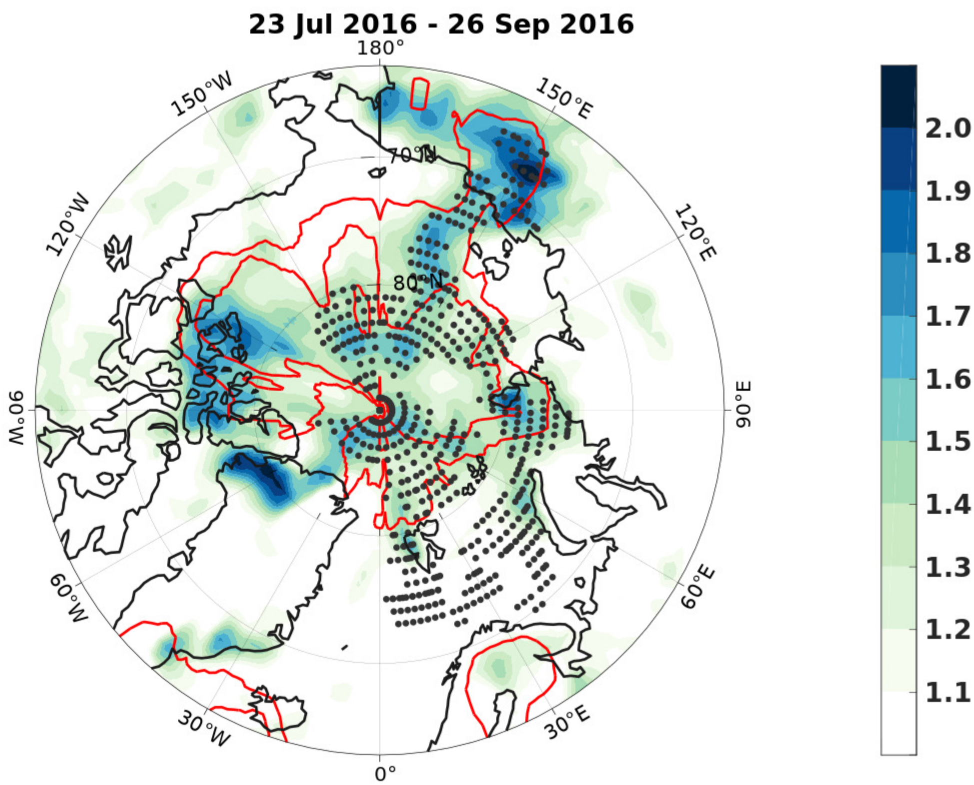
Figure 7 Each of the four panels depicts an exemplary patch, labelled by ~~a~~ the respective panel's letter in Fig. 6. Time periods ~~in~~ on the abscissa span from the earliest (day 1) ~~and~~ to the latest date (e.g. day 170 in panel A) of all extreme seasons of the grid points that compose each patch. The upper part of each panel shows time series of daily precipitation, accumulated for all grid points that compose the patch. Given that the patch period ~~in~~ on the abscissa is composed by non-identical extreme seasons per grid point, the time series in the middle of each panel shows the fraction of the ~~percentage of~~ extreme ~~seasons~~ season patch that includes ~~each day in abscissa~~the respective day. The lower part of the panel marks each day by a vertical line if a weather system overlapped with the patch (see text): red for cyclones, blue for WCBs, green for TMEs and brown for RWB. Central date and average latitude/longitude of each of the four patch is shown under the panels.



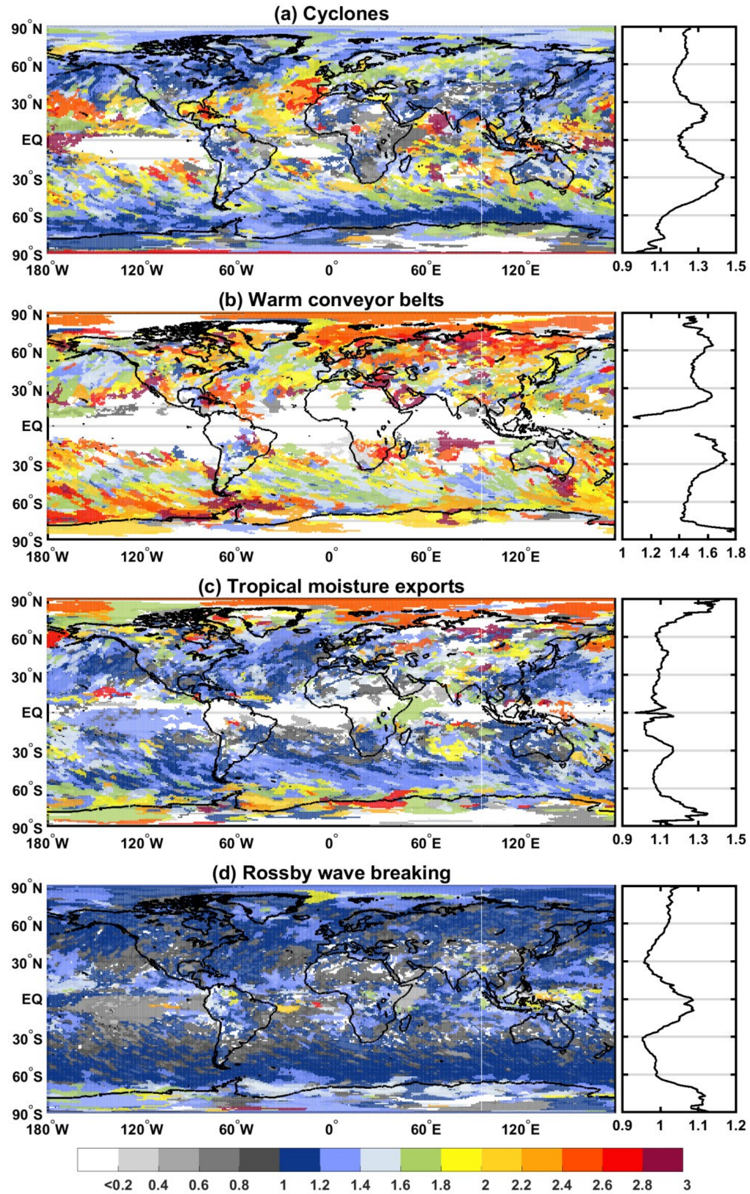
~~**Figure 8 (a)** Accumulated precipitation from 27 November 1992 to 1 March 1993 (in colour), cyclone frequency is shown in red contours (with an interval value of 5%, starting from 10%) and TME frequency is shown in green contour (with an interval of 5%, starting from 20%). Feature frequencies are calculated on the basis of six-hourly outputs from ERAI. **(b)** as in **(a)** but for different period and region. **(c)** 24-hour accumulation of precipitation from 28 December 1992, 1200 UTC to 29 December 1992 1200 UTC (in colour). Red contours show sea level pressure on 29 December 1992 0000 UTC (starting from 1015 hPa and with a step of -3 hPa). Green contour shows the areas co-locating with TMEs and blue contour shows WCB ascent objects. In all panels, the spatial extent of the patches are represented by the hatched area.~~**Figure 8 (a)** Ratio of accumulated precipitation during the period 27 November 1992 to 1 March 1993 with respect to climatological values for the same time period (in colour) for an extreme wet season patch affecting the US west coast (dotted area). Red (green) contours show areas with positive anomalies of cyclone (TME) occurrences with respect to climatology. Contours start from 5% and have a 5% of interval. **(b)** as **(a)** but for the period 2 October 1989 to 9 January 1990 for an extreme wet season patch affecting the Iberian Peninsula (dotted area). **(c)** 24-hour accumulation of precipitation from 1200 UTC 28 December 1992 to 1200 UTC 29 December 1992 (in colour). Red contours show sea level pressure at 0000 UTC 29 December 1992 (starting from 1015 hPa and with a step of -3 hPa). Green contours show areas with TMEs and blue contours shows areas with WCB ascent. **(d)** as in **(c)** but at 0000 UTC 26 December 1989.



~~**Figure 9** Accumulated precipitation from 27 November 2010 to 3 April 2011 (in colour). The frequency of cyclones occurrence during this period is shown in red contours for values of 20, 40 and 60%, while the brown contour shows Rossby wave breaking frequency exceeding 60%. Feature frequencies are calculated on the basis of six-hourly outputs from ERAI. The grey dashed line shows the track of tropical cyclone Yasi, while its position on 5 February 2011, 18 UTC, is represented by the red dot. The spatial extent of the patch is represented by the hatched area.~~ **Figure 9 (a)** Ratio of accumulated precipitation during the period 27 November 2010 to 3 April 2011 with respect to climatological values for the same time period (in colour) for an extreme wet season patch affecting Australia (dotted area). Red (green) contours show areas with positive anomalies of cyclone (RWB) occurrences with respect to climatology (shown are anomalies of 10 and 20% for cyclones and 20% for RWB). **(b)** 24-hour accumulation of precipitation from 1800 UTC 3 February to 1800 UTC 4 February 2011 (in colour). Red contours show sea level pressure at 1800 UTC 4 February 2011 (starting from 1006 hPa and with steps of -2 hPa). The grey dashed line shows the track of tropical cyclone Yasi, while its position of cyclolysis is represented by the cross symbol.



~~**Figure 10** Ratio of accumulated precipitation during the period 23 July 2016 to 26 September 2016 and the climatological values of same dates (in colour). Red contours show the areas where the climatological ratio of cyclones occurrence is 1.25 and 1.5. The spatial extent of the patch is represented by the dotted area.~~ **Figure 10** Ratio of accumulated precipitation during the period 23 July 2016 to 26 September 2016 with respect to climatological values for the same time period (in colour). Red contours show areas with positive anomalies of cyclone occurrences with respect to climatology (shown are contours of 5 and 10%). The spatial extent of the patch is represented by the dotted area.



~~**Figure 12** All patches are coloured according to their overlapping frequency ratios with specific weather systems. Panels in the right column show the latitudinal distribution of the overlapping ratios, as zonal averages within +/- 7.5° in latitude. Patches may overlap between each other and thus illustration started from the patch presenting the lowest ratio.~~ **Figure 11** All extreme wet season patches are coloured according to their overlapping frequency ratios with specific weather systems (relative to the climatology). Panels in the right column show the latitudinal distribution of the overlapping ratios, as zonal averages within +/- 7.5° latitude. Patches may overlap between each other; to allow higher visibility for patches with highest ratios, the overlay of the patches in all panels started from the patch with the lowest ratio.