Projected changes in hot, dry and wet extreme events’ clusters in CMIP6 multi-model ensemble

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Abstract
Concurrent extreme events, i.e. multi-variate extremes, can be associated with strong impacts. Hence, an understanding of how such events are changing in a warming climate is helpful to avoid some associated climate change impacts and better prepare for them. In this article, we analyse the projected occurrence of hot, dry, and wet extreme events’ clusters in the multi-model ensemble of the 6th phase of the Coupled Model Intercomparison Project (CMIP6). Changes in ‘extreme extremes’, i.e. events with only 1% probability of occurrence in the current climate are analysed, first as univariate extremes, and then when co-occurring with other types of extremes (i.e. events clusters) within the same week, month or year. The projections are analysed for present-day climate (+1 °C) and different levels of additional global warming (+1.5 °C, +2 °C, +3 °C). The results reveal substantial risk of occurrence of extreme events’ clusters of different types across the globe at higher global warming levels. Hotspot regions for hot and dry clusters are mainly found in Brazil, i.e. in the Northeast and the Amazon rain forest, the Mediterranean region, and Southern Africa. Hotspot regions for wet and hot clusters are found in tropical Africa but also in the Sahel region, Indonesia, and in mountainous regions such as the Andes and the Himalaya.

1. Introduction
Compound events, i.e. multivariate extremes, count among the most potentially impactful consequences of human-induced climate change (Zscheischler et al 2018), but have received relatively little attention in the research literature so far. In particular, dedicated analyses of projected changes in compound events are very limited, although the impacts could be much stronger than those caused by isolated hazards. Some studies investigate the occurrence of compound events in present climate (Martius et al 2016) or in the recent past (AghaKouchak et al 2014), while others have investigated projections of changes in multivariate extreme conditions (Zscheischler and Seneviratne 2017), but without an event perspective. For example, the co-occurrence of hot and dry conditions can intensify the development of summer heatwaves (Seneviratne et al 2010) and can also be associated with specific hazards, such as fire risk (Zscheischler et al 2018). In addition, the fact that compound events can result from correlated extremes implies that their probability can be higher than expected by chance (Zscheischler and Seneviratne 2017). For instance, the 2010 heatwave and drought over Russian Federation was a factor up to five more likely than if the probability of dry and hot conditions had been uncorrelated in the region (Zscheischler and Seneviratne 2017). Accounting for the multivariate likelihood of compound events can also increase their predictability. There is so far to our knowledge no analyses of projected changes in compound extreme events available based on the new 6th phase of the Coupled Model Intercomparison Project (CMIP6; Eyring et al 2016), which serves as the basis for the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6).

Here, we analyse projected changes in ‘extreme extremes’ – by which we refer to extremes that occur with only 1% probability—in the CMIP6 multi-model ensemble at four different global warming levels, i.e. +1 °C (present-day warming; IPCC 2018), +1.5 °C, +2 °C, +3 °C. Furthermore, we investigate projected changes in clusters of different extremes, i.e. extreme hot and dry events and extreme hot and wet events that co-occur in the same
week, month, or year. Such events’ clusters are of high relevance for expected impacts in regions where different extremes co-occur, since it implies little time for recovery in between extreme events in the affected regions.

2. Methods

2.1. Climate models

We use CMIP6 simulations from 8 Earth System Models for historical (1850–2015) and future (2016–2100) time frames. We thereby focus on a shared socioeconomic pathway (SSP) with high mitigation challenge and low adaptation challenge, resulting in high emissions: SSP5-8.5 (O’Neill et al. 2017). We analyse the projections at different global warming levels, using the ‘Empirical Scaling Relationship’ (ESR) approach (Seneviratne et al. 2018, Hoegh-Guldberg et al. 2018). The ESR approach makes use of the fact that climate change projections at different global warming levels were found to be only little affected by details of the underlying emissions scenarios (Seneviratne et al. 2016, Seneviratne et al. 2018, Wartenburger et al. 2017). This means that, although the analysed simulations are based on the SSP5-8.5 scenario, the results would likely be similar for other SSPs (given that they reach the targeted warming).

From the analysed simulations, one ensemble member is used per model. We analyse daily near-surface air temperature (tas) and precipitation (pr) over land to compute hot, dry, and wet extremes. The complete list of models is provided in the appendix table A1. While we mostly present our results as global maps, we illustrate the inter-model spread for regions defined in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; Seneviratne et al. 2012), see figure A1.

2.2. Definition of ‘extreme’ hot, wet and dry days

In this study, we analyse ‘extreme extremes’, i.e. events with only 1‰ probability of occurrence in the reference period. We thereby focus on hot, wet, and dry conditions. Our analysis is based on exceedance over/below a quantile-based threshold. First, we calculate the threshold for each index, model, and grid point in our reference period. We then determine the number of extreme events by counting exceedances over/below the threshold for four different global warming levels.

To determine hot extremes, we compute the 99.9 th percentile of temperature for each grid cell for the reference period. A hot day is then defined as a day that exceeds the 99.9 th percentile temperature distribution at different warming levels.

For wet extremes, we aggregate precipitation over 5 days, where the date is assigned to the last day of the 5 day period. From the running 5-day sum we then compute the 99.9 th percentile in the reference period. Finally, a wet day is defined as a day that exceeds the 99.9 th percentile precipitation distribution at different warming levels.

To compute dry days we first aggregate precipitation over 90 days and then compute the 0.1 th percentile in the reference period. Note that the date of the running sum is the last day of the 90 day period. A dry day is then defined as a day where precipitation falls below the 0.1 th percentile.

The reference period for each model is defined as the first 20-year period where global mean warming exceeds +0.61 °C with respect to 1850–1900. This warming approximately corresponds to the observed warming between 1850–1900 and 1986–2005 (IPCC 2013). As warming levels, we consider +1 °C, +1.5 °C, +2 °C, and +3 °C. The +1 °C warming level approximately corresponds to present-day warming in 2018 (IPCC 2018). Global warming levels of +1.5 °C and +2 °C refer to the targets from the Paris Agreement (UNFCCC 2015), whereby the agreement aims at most at limiting global warming ‘well below +2 °C. A global warming of +3 °C corresponds to the warming that is projected to be reached at the end of the 21st century, given the current nationally-determined mitigation ambitions (IPCC 2018). The timing of the reference period and the global warming levels in the different CMIP6 simulations is determined by the first 20-year period where global mean warming exceeds the respective warming level (see Hauser et al. 2019) for details). To compare results from different models, we apply a second-order conservative remapping on a common 2.5° × 2.5° grid and compute the multi-model median.

2.3. Definition of extreme events’ clusters

To estimate the co-occurrence of ‘extreme’ hot, dry and wet events, we build event clusters for all event types. This results in four types of extreme events’ clusters: (1) hot and wet, (2) hot and dry, (3) dry and wet, and (4) hot, dry and, wet events. We focus on cluster types (1) and (2) as we find very small probabilities of occurrence for categories (3) and (4). Results for cluster types (3) and (4) are provided in the appendix (figures A2 and A3). We define co-occurrence for different time scales at every location. In particular, we identify events that co-occur in the same week, in the same month, or the same year, at each location for each 20-year period at the four global warming levels and for each CMIP6 model. Hence, for each global warming level, there could be at maximum 20 events in the case of the yearly clusters, 240 events for the monthly clusters, and 1043 events for the weekly clusters. Note that for co-occurring of dry and hot extreme in the same week or month we might not capture compound long-lasting droughts and hot extremes, that occur on different timescales.
3. Results

3.1. Univariate events
The number of expected univariate events in the reference period (+0.61 °C) is 8 events (1‰ · 365 · 20). We find a strong increase in extreme hot days with increasing global warming levels (figure 1(a)). Already for +1 °C of global warming (figure 1(a), top), which approximately corresponds to present-day warming, we find more than a doubling of hot extremes (for the multi-model median) compared to +0.61 °C in most regions of the world. The projected increase of extreme hot days amplifies for higher warming levels, particularly in tropical regions and the Sahel. We find substantial differences between +1.5 °C and +2 °C warming (figure 1(a), middle). For +1.5 °C of global warming, numerous regions experience around 100 extreme hot days in 20 years. In tropical regions, the number of extreme hot days can even reach 250 days in 20 years – 30 times more than in the reference. For +2 °C of global warming, maximum values in tropical regions reach up to 1000 days. In many mid-latitude regions, around 50 extreme hot days are projected to occur, which corresponds to an increase by a factor 7 compared to the reference period. For +3 °C warming, we find a further increase in the occurrences of extreme hot days (figure 1(a), bottom). Even in the mid-latitudes, more than 100 extreme hot days within 20 years are projected to occur. We note, however, that the spread between the models can be large (figure A4(a)) and regions with a large signal also show an especially large spread. Nonetheless, even considering this large inter-model spread, the tropical hot-spot regions show a much larger increase than the other regions.

For extreme dry days, regional hotspots evolve for higher global warming levels (figure 1(b)). For +1 °C warming, a doubling of extreme dry days is detected in parts of Southern Asia, the Mediterranean, the Amazonian region and Northeastern Brazil (figure 1(b), top). For +1.5 °C of global warming (figure 1(b), middle), around 70 dry days are projected at various locations. This corresponds to nearly 10 times more dry days than during the reference period. For +2 °C warming between 80 and 120 extreme dry days are projected in parts of the Mediterranean, the Amazonian region and Northeastern Brazil (figure 1(b), middle). These hotspots become even more pronounced for +3 °C of global warming with up to 200 dry days in 20 years (figure 1(b), bottom). Hence, at these locations, the probability of extreme dry days to occur for +3 °C warming is 25 times larger compared to the reference period with +0.61 °C warming. Again, there is a large inter-model spread for some regions (figure A4(b)). The region with the largest spread is Northeastern Brazil, one model reports 46 extreme dry days in 20 years.
Figure 2. Joint occurrence of ‘extreme’ hot and dry days, (a) in the same year, (b) in the same month and (c) in the same week at different warming levels.

(minimum), while the maximum over all models is 545 and the median is 179.

The occurrence of extreme wet days shows a slight increase over most of the land regions for +1 °C compared to +0.61 °C (figure 1(c), top). With increasing warming levels, extreme wet days are particularly increasing in tropical Africa and partly in the Sahel region. For +1.5 °C, up to 32 extreme wet days per 20 years are projected to occur in this region (figure 1(c), middle). More than a doubling of extreme wet days compared to the reference period is also projected in parts of Central South America and Southeast Asia. Under a global warming of +2 °C, the number of projected extreme wet days reaches 43 days per 20 years in tropical Africa and the Sahel (figure 1(c), middle). For +3°C of global warming, the occurrence of extreme wet days is further strengthened in the hotspots (figure 1(c), bottom). In tropical Africa and the Sahel, the number of extreme wet days varies between 30 and 60 days per 20 years. Also, in Central South America, up to 60 extreme wet days per 20 years, are projected to occur. This implies an increase of the wettest extremes by a factor of around 8 compared to the reference period.

3.2. Clustered ‘extreme hot and dry’ events
The occurrence of clustered extremes is of particular relevance to impacts. Here, we first analyse results for clusters of joint hot and dry extremes that co-occur in the same year, month, or week (figure 2). The probability of co-occurrence of the events is much lower than the occurrence of the single events. However, we find a substantial increase of the co-occurrence of extreme hot and dry days with higher global warming levels across all timescales. Our results suggest that particularly the projected dry hotspots such as the Amazonian region, Northeastern Brazil and the Mediterranean would also experience joint very hot and dry conditions under higher global warming levels.

For +1 °C of global warming (i.e. present-day conditions), the co-occurrence of hot and dry extremes is very limited. In some regions there is on average only one year with clustered dry and hot events within 20 years. The numbers are much smaller for monthly clusters, and nearly no weekly clusters are found across the whole globe.

At +1.5 °C of global warming up to 3 yearly clusters of extreme hot and dry days are simulated in Northeastern Brazil in 20-years. It is interesting to note that the numbers are the same for the weekly clusters, showing that these yearly clustered events are occurring within the same week. For +2 °C of global warming, the multi-model median shows a maximum of 5 co-occurring hot and dry clusters in the same year per 20 years and more than 7 events in the same week per 20 years in Northeastern Brazil. Hence, on average, every four years in Northeastern Brazil could be hit by co-occurring extreme hot and dry events.
Figure 3. Joint occurrence of ‘extreme’ hot and wet days, (a) in the same year, (b) in the same month and (c) in the same week at different warming levels.

3.3. Clustered ‘extreme hot and wet’ events

For compound extreme hot and wet days, we find a small probability for events to co-occur at low global warming levels (figure 3 and figure A6 for regional averages at a warming of +3 °C). At +1 °C of global warming (i.e. present-day conditions), there is no more than 2 years per 20 years displaying both hot and wet events at any location. For clustered hot and wet events in the same month or the same week, nearly no clusters are simulated. However, the likelihood of hot and dry events in the same year is increasing with higher global warming levels.

At +1.5 °C of global warming, up to 4 years with clustered hot and wet events are projected to occur per 20 years in tropical Africa, the Sahel and Southeast Asia (Indonesia). For +2 °C of global warming, 8 years with clustered hot and wet extreme events are projected to occur per 20 years in these regions. Other hotspots for hot and wet events are projected in mountainous regions such as in the Andes in South America and in the Himalaya in Central Asia.

For +3 °C of global warming, the number of events in mountainous regions (e.g. Andes, Himalaya) increase to up to 10 years with clustered events per 20 years, i.e. every second year displays both wet and hot events. This is an increase by at least a factor of 6 compared to conditions for present-day global warming of +1 °C.

Considering changes in extreme hot and wet days that occur in the same month or week, we also find a strong increase for higher global warming levels. However, maximum values are lower than for the co-occurrence in the same year, indicating that the timing of the events is often shifted by a few weeks or months. At +2 °C of global warming, the maximum number of events in the same month is around 3 events per 20 years at single locations, for example, in...
tropical regions such as Indonesia and Peru and the Subtropics/ Sahel in Niger. At +3 °C of global warming, we find maximum values of up to 10 months with clustered hot and wet extreme events per 20 years. For events that co-occur in the same week, we again find mountainous regions and Indonesia as hotspots with more than 4 events. We detect a smaller number of co-occurring extreme hot and wet extremes in the same week than in the same year, particularly in tropical Africa.

4. Discussion

Our results highlight the following main results. First, we focus on very ‘extreme extremes’ that have only a 1‰ probability of occurrence. We find that these ‘extreme extremes’ for hot, dry, and wet conditions display very strong increases with higher levels of global warming when assessed as univariate extremes. This is consistent with previous results, which have shown that rarest events tend to show the highest proportional increase in frequency with increasing global warming levels (Kharin et al 2018, Hoegh-Guldberg et al 2018, Fischer and Knutti 2015). Note that we focus on ‘extreme extremes’ on land, and the stronger warming of the land surface compared to the ocean surface can already partly explain why we expect to have stronger increase of hot extremes than global mean temperature. For +1 °C (+3 °C) global warming land mean temperatures increased on average by +1.3 °C (+5.4 °C) (table A2).

We then analysed bivariate clustered hot and dry and hot and wet events, which either happen in the same year, same month or the same week, at different levels of global warming. These clustered events are highly relevant for impacts because they imply that the same regions could face recurrent extremes which may leave little time for recovery between occurrences. In addition, when extreme conditions occur at the same time, e.g. within the same week, higher impacts may result from interacting conditions, such as dry and hot conditions leading to more fire risk (Zscheischler et al 2018, Abatzoglou et al 2019) or agricultural loss (Toreti et al 2019). We find that in hotspot regions such as the Amazonian region and Northeastern Brazil, the probability of occurrence of hot and dry days clusters nearly doubles when global warming levels increase from +1.5 °C to +2 °C and from +2 °C to +3 °C warming. Some modeled hotspots of hot and dry event clusters can also be observed in the current climate. Observational studies show that the El Niño/Southern Oscillation (ENSO) can contribute to this co-occurrence in the Amazonian region, e.g. in Brazil (Hao et al 2018, Jimenez-Munoz et al 2016). In addition, deforestation can increase drought conditions in these regions (de Oliveira et al 2019), which could increase the probability of dry and hot events in a warming climate.

Furthermore, our analysis shows that clustered dry and hot events are more frequent than hot and wet events. This can be understood by the fact that dry and hot events are often co-occurring because they are occasioned by similar atmospheric conditions (e.g. high-pressure systems) and additionally reinforce one another (Seneviratne et al 2010, Berg et al 2015, Zscheischler and Seneviratne 2017). This is also consistent with the fact that the identified yearly dry and hot clusters are often identical to the weekly clusters (figure 2 (a)). In particular, these clusters can be found in the Himalayan region in Asia and the Andes region in South America for high global warming levels.

Note that climate models have problems to reliably capture precipitation and show particularly too dry conditions in the Amazonian region (Flato et al 2013). This could lead to an overestimation of dry conditions in the tropical regions (O’Gorman and Schneider 2009). It was also shown that this mean dry bias is co-located with a mean warm bias in the region and other locations (Mueller and Seneviratne 2014). It should be noted that, since we focus on ‘extreme extreme’ (1‰ probability), these events have by design a very limited probability to occur individually and are even less likely to co-occur at weekly, monthly or yearly scale. This may potentially underestimate future impacts as even less pronounced extremes may be associated with strong impacts. This is, in particular, the case for compound events, which may be the result of co-occurring non-extreme conditions (Seneviratne et al 2012), whereby only the co-occurrence is rare. Hence, future studies could also apply lower thresholds to estimate extreme cluster events. Furthermore, one could also apply a minimum duration criterion taking into account potentially associated impacts or consider the magnitude of the events.

5. Conclusions

In this study, we have analysed projected changes in ‘extreme extreme’, i.e. extremes with only 1‰ probability of occurrence, as well as their projected occurrence as compound events’ clusters in the same year, same month, or the same week, based on the new CMIP6 multi-model experiment. The projections are analysed for present-day climate conditions (+1 °C), as well as for different levels of higher global warming (+1.5 °C, +2 °C, +3 °C).

Our results show that the risk of occurrence of ‘extreme extremes’ strongly increases with higher global warming levels, and that the co-occurrence of extreme clusters also substantially increases with global warming in some regions. Hotspot regions for increased occurrence of hot and dry clusters are found in Brazil (mainly in the Northeast and the Amazon), the Mediterranean region, and Southern Africa. Hotspot regions for increased occurrence of wet and hot
Table A1. Overview of CMIP6 models used in this study, the modelling institutions providing them, and the ensemble members employed.

| Model name          | Modelling center                                                                 | member       |
|---------------------|----------------------------------------------------------------------------------|--------------|
| BCC-CSM2-MR         | Beijing Climate Center, China                                                     | r1i1p1f1     |
| CanESM5             | Canadian Centre for Climate Modelling and Analysis                               | r1i1p2f1     |
| CNRM-CM6-1          | Centre National de Recherches Météorologiques, France/ Centre Européen de        | r1i1p1f2     |
|                     | Recherche et Formation Avancée en Calcul Scientifique, France                    |              |
| CNRM-ESM2-1         | Centre National de Recherches Météorologiques, France/ Centre Européen de        | r1i1p1f2     |
|                     | Recherche et Formation Avancée en Calcul Scientifique, France                    |              |
| INM-CM4-8           | Institute for Numerical Mathematics, Russian Academy of Science, Russian Federation | r1i1p1f1     |
| INM-CM5-0           | Institute for Numerical Mathematics, Russian Academy of Science, Russian Federation | r1i1p1f1     |
| IPSL-CM6A-LR        | Institut Pierre Simon Laplace, France                                            | r1i1p1f1     |
| NESM3               | Nanjing University of Information Science and Technology, China                  | r1i1p1f1     |

Figure A1. Regions defined in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; Seneviratne et al 2012).

Table A2. Land mean temperature (excluding Antarctica) at different warming levels for individual models and the multi-model mean.

| Model name          | 1.0°C  | 1.5°C  | 2.0°C  | 3.0°C  |
|---------------------|--------|--------|--------|--------|
| BCC-CSM2-MR         | 1.46   | 2.06   | 2.78   | –      |
| CNRM-CM6-1          | 1.24   | 1.91   | 2.54   | 5.27   |
| CNRM-ESM2-1         | 1.26   | 1.99   | 2.67   | 5.32   |
| CanESM5             | 1.34   | 2.09   | 2.76   | 5.53   |
| INM-CM4-8           | 1.21   | 1.88   | 2.61   | –      |
| INM-CM5-0           | 1.33   | 2.01   | 2.69   | –      |
| IPSL-CM6A-LR        | 1.42   | 2.08   | 2.75   | 5.50   |
| NESM3               | 1.27   | 1.94   | 2.70   | 5.34   |
| mean                | 1.31   | 2.00   | 2.69   | 5.39   |

Clusters are found in tropical regions, partly in the Sahel region, and in mountainous regions such as the Andes and the Himalayan region. The dry and hot clustered events are generally the same for the weekly and yearly clusters, showing that these conditions are generally co-occurring. On the other hand, the wet and hot event clusters are generally different at yearly vs. monthly and weekly time scales, showing that these conditions are less likely to co-occur at the same time. This can be understood by the fact that dry and hot conditions are often meteorologically related.

These analyses highlight that human-induced global warming leads to substantial risks of increases in extreme types (‘extreme extreme’ and clustered extremes) that have received little attention in the research literature so far, and were to our knowledge assessed here for the first time in the CMIP6 multi-model ensemble. The findings show that these risks should be carefully evaluated as they may disproportionately lead to impacts due to the extremeness of the considered events as well as the additional impacts associated with compound and clustered extreme events. Our results also show that strong mitigation and a stabilization of CO$_2$ emissions consistent with the aims of the Paris Agreement (i.e. limiting global warming to ‘well below $+2^\circ$C’) would substantially limit the risks associated with increases in very rare extreme events and their co-occurrence as events’ clusters in single years, months or weeks.
Figure A2. Joint occurrence of ‘extreme’ dry and wet days, (a) in the same year, (b) in the same month and (c) in the same week at different warming levels.

Figure A3. Joint occurrence of ‘extreme’ hot and dry and wet days, (a) in the same year, (b) in the same month and (c) in the same week at different warming levels.
Figure A4. Box plots showing the inter-model spread for the univariate extremes, namely extreme hot days (a), extreme dry days (b), and extreme wet days (c) at a warming level of +3 °C. Displayed are the 26 SREX regions (figure A1). The orange line depicts the multi-model median, the box the interquartile range (IQR), and whiskers extend from the 5th to the 95th percentile.

Figure A5. As figure A4 but for extreme hot and dry events in the same year (a), in the same month (b), and in the same week (c).
Figure A6. As figure A4 but for extreme hot and wet events in the same year (a), in the same month (b), and in the same week (c).

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Appendix A

This appendix includes supplementary tables A1 and A2 and figures A1 and A6.

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