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Key Points:
- Precipitation variability is projected to increase globally
- Northern hemisphere midlatitudes are a key region for worsening pluvials
- Drying regions may see more pluvials that are longer and stronger

Supporting Information:
- Supporting Information S1

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Future Projections of Global Pluvial and Drought Event Characteristics

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Abstract This study assesses projections from 24 CMIP5 models of number, duration, and severity of pluvial and drought events utilizing 6-month standardized precipitation index. Increased variability of standardized precipitation index is projected globally. More frequent, longer lasting, and stronger pluvials are projected in wet regions, and the same for droughts in dry regions. Worsening pluvials and droughts are most apparent in the Northern Hemisphere midlatitudes and the Americas, respectively. Uniquely, this study investigates pluvials and droughts in locations where the precipitation trend is of the opposite sign. In drying regions, 40% of grid points project an increase in number and 65% project an increase in duration of severe pluvials. Projections for severe drought events in wetting regions show similar projections. As precipitation trends alone do not provide information about pluvial and drought characteristics this study has important implications for planning and resilience.

Plain Language Summary The variability of precipitation is projected to increase globally in the future, which has a multitude of impacts including on water resources, agriculture, public health, and fire outbreaks. This study uses future projections from global climate models to evaluate how the number, duration, and severity of extended wet periods (pluvials) and dry periods (drought) will change in the future for the first time. More frequent, longer lasting, and stronger pluvials are projected in wet regions of the world, and the same for droughts in dry regions. The Americas, including Central America, the Caribbean, and the Amazon, are a hot spot for worsening droughts, and northern North America and Europe are hot spots for worsening pluvials. Uniquely, this study investigates pluvials and droughts in locations where the precipitation trend is of the opposite sign. For the most severe pluvial events, almost half of locations with a drying trend showed an increase in number of pluvials and 65% of locations showed an increase in duration. Projections for severe drought events in wetting regions show similar projections. As mean precipitation trends alone do not provide information about pluvial and drought characteristics this study has important implications for planning and resilience.

1. Introduction

Pluvial and drought events have large socioeconomic impacts around the world. Impacts from excessive rainfall, or pluvials, include human and agricultural loses from flooding, waterborne disease outbreaks, and the buildup of vegetation that can be a fire hazard in later seasons (e.g., Auld et al., 2004; Bronstert, 2003; Govender et al., 2006). Impacts from drought include reduced surface and ground water resources, crop failure, and tree mortality (e.g., Anderegg et al., 2013; Epule et al., 2014; Li et al., 2009). With increased precipitation variability in a warmer climate (e.g., Pendergrass et al., 2017; Räisänen, 2002; Rind et al., 1989), changes in characteristics of pluvial and drought events (e.g., number, duration, and severity) might be expected. In order to increase resilience to these events, it is necessary to understand how these wet and dry periods will change in the future.

Much prior work has focused on changes in drought characteristics. Recent studies, including those using models from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012, show increasing drought frequency, especially for the most extreme droughts in subtropical regions (e.g., Cook et al., 2014; Dai & Zhao, 2017; Hunt, 2011; Orlowsky & Seneviratne, 2013; Touma et al., 2015). However, there has been much less focus on how the characteristics of extended wet periods, or pluvials will change in the future. While we expect the most intense rain events to increase (e.g., O'Gorman & Schneider, 2009), it is not known if this will be true for pluvials, like the May 2015 heavy rainfall event in Oklahoma and Texas. May 2015 was the wettest month on record (since 1895) for both states and was a the major cause for Oklahoma and Texas to become drought free for the first time since 2010 (NOAA, 2016). Studies that have looked at droughts and pluvials together such as Kangas and Brown (2007), highlighted that the largest annual drought and pluvial events occur more frequently in the central United States, and drought-pluvial dipoles have also been highlighted in the Great Plains (Christian et al., 2015). Duffy et al. (2015) investigated dry and wet periods in the Amazon and noted that the characteristics of projected future drought and pluvials are best understood in the context of projected changes in mean precipitation.

As there have been no global studies of how the characteristics of pluvial events at less than interannual scales are projected to change in the future, this study quantifies those changes with the CMIP5 archive and makes comparisons with changes to drought characteristics. Importantly, this study will put changes in frequency, severity, and duration of pluvials in the context of future precipitation trends. A description of the data sets and definitions are found in section 2, with results for the characteristics of pluvial and drought events shown in section 3.

2. Data and Methods

Observations of precipitation from two land-only monthly data sets are used for the historical period; Climate Research Unit (CRU) TS v3.23 precipitation at 0.5° resolution from 1901 to 2014 (Harris et al., 2014) and Global Precipitation Climatology Center (GPCC) v7 precipitation at 1° resolution from 1901 to 2015 (Schneider et al., 2011). Historical and future projection (representative concentration pathway; RCP4.5 and RCP8.5) simulations are used from 24 CMIP5 models (see Table S1 in the supporting information for model details), with one ensemble member per model used. Results from the more moderate RCP4.5 scenario are similar, but magnitudes are smaller (see supporting information). Model horizontal resolution ranges from 0.75° to 2.8°, and data are regridded bilinearly to a common 2° horizontal resolution between 70 N and S to facilitate comparison, as is commonly done in multimodel analysis (e.g., Martin et al., 2014). Observational data sets are used at their native resolution. Changes in future characteristics are established using differences between 2080-2100 RCP output and 1980–2000 historical output. Statistical significance is measured using a Student's *t* test at the 95% level for observations, and model spread assessed using the number of models that agree on the sign of the trend.

There is no singular definition of pluvials nor droughts (Wilhite & Glantz, 1985). To identify meteorological pluvial and drought events, this study uses the 6-month standardized precipitation index (SPI; McKee et al., 1993). SPI is calculated at each grid point, for each observational data set and model, for the duration of the observations (1901–2015) and the model output (1900–2100). SPI has thresholds for precipitation deficits and excesses, making it of particular use for this study. Pluvial (positive) and drought (negative) and events are defined based on exceedence of two thresholds: moderate (± 1) and severe (± 2). For each category (moderate or severe) and for pluvials and droughts, we define (1) an event occurrence as a continuous period of time when the SPI exceeds that level, (2) the duration as the length of an event in months, and (3) the intensity as the average SPI during an event. As the 6-month SPI is used, the thresholds only need to be exceeded for 1-month to be identified as an event. As some water management decisions are influenced by the intensity and duration of an event, we calculate a "severity index" (SI), based on Peters (2014), which combines the two variables. The index is given by

$$SI = \frac{\sum_{i=1}^{n} SPI_i \times T_{event}}{\overline{SPI} \times \bar{T}} \tag{1}$$

where SPI_i is the monthly SPI during the event, T_{event} is the number of months during which the SPI exceeds the appropriate threshold, $\overline{SPI}$ is the mean value of all the months that SPI exceeds the threshold, and $\bar{T}$ is the mean duration of all the events that exceed the threshold.

3. Results

3.1. Climatology and Trends

In the 20th century, both observational data sets show similar trends in precipitation across the globe (Figure S1). Significant increases in precipitation are observed across the midlatitudes and decreasing trends across large sections of the subtropics. The CMIP5 models represent the general spatial patterns of the observed trends in the historical period. Projections for the 21st century (Figure 1a), continue the observed

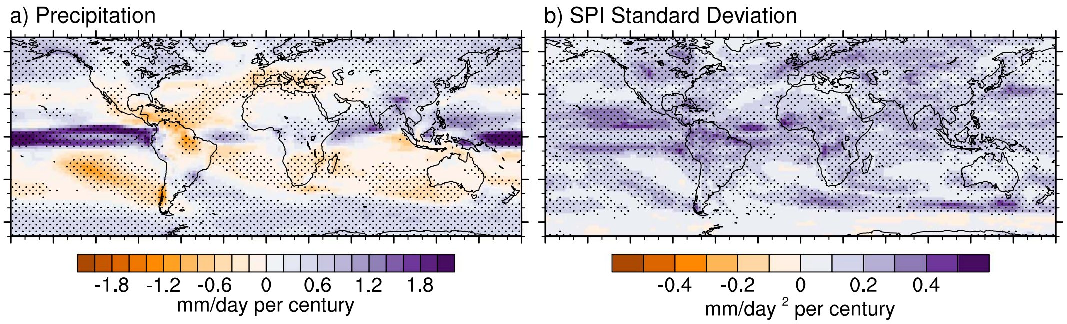

Figure 1. Multimodel mean trends (RCP8.5 2006–2100) in (a) precipitation and (b) 9-year running standard deviation in SPI. Stippling indicates regions where at least 18 of the CMIP5 models agree on the sign of the trend. SPI = standardized precipitation index; RCP = representative concentration pathway; CMIP5 = Coupled Model Intercomparison Project Phase 5.

trends of wetting in the deep tropics and midlatitudes, and drying in the subtropics, with a large number of models agreeing on this pattern as seen in prior studies (Collins et al., 2013).

The distribution of SPI from CRU, GPCC, and CMIP5 historical simulations is shown in Figure 2 and illustrates the historical simulations capability in replicating the observed probability distribution function (results are similar for land only as shown in Figure S2). The GPCC and CMIP5 historical multimodel mean have narrower distributions than CRU, which is likely due to the higher spatial resolution of CRU being able to resolve more extremes. In the future, the SPI mean shifts to the right (becoming wetter) and widens (more extremes), implying more variability.

Despite the model and observations agreeing on historical trends in mean precipitation (and SPI, not shown), the trend in variability of SPI shows a very different spatial signal. As shown in Figure 1b, interannual precipitation variability, as measured by the 9-year running standard deviation of the SPI, shows an increasing trend across almost the entire globe in the 21st century, even in regions that are projected to become drier, such as Central America, the Intra-America Seas, Southern Africa, and the southwest United States (Figure 1a). The largest increases in variability, with highest model agreement, are seen in the tropics and midlatitudes, and the smallest increases (and decreases in some locations) with less model agreement, are in the subtropical ocean basins where precipitation is low. This pattern matches well with those shown in Pendergrass et al. (2017), which uses a different definition of variability. The increasing variability globally suggests more frequent pluvial and drought events will occur in the future.

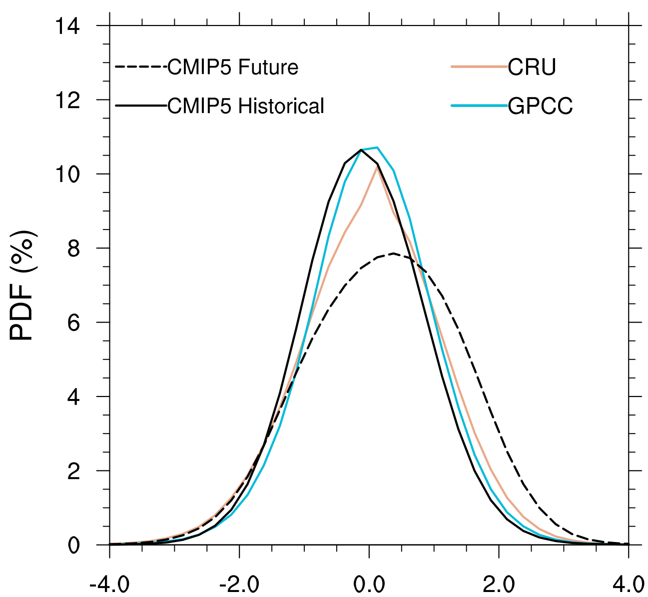

Figure 2. Probability distribution functions of standardized precipitation index from observations (brown and blue) and CMIP5 simulations (black) of the past (solid) and future (dashed) for all grid points. Observational and historical CMIP5 simulations are for 1980–2000 and future CMIP5 simulations (RCP8.5) are 2080–2100. CMIP5 = Coupled Model Intercomparison Project Phase 5; RCP = representative concentration pathway; CRU = Climate Research Unit; PDF = probability density function; GPCC = Global Precipitation Climatology Center.

Interestingly, there is much less agreement in the trend of SPI variability between the two observational data sets, and the CMIP5 historical simulations (Figure S2). The CMIP5 historical multimodel mean shows almost zero variability trend in the 20th century, whereas the observations show large trends, but they do not agree with each other in many locations. Across the US, both observations show increased variability (except in the south central United States), but in some locations, northern Canada and central Asia in particular, the trends are large and opposite. Agreement is better when observational data sets are limited to 1930 onwards (not shown) but disagreements in sign are still evident. Differences in variability at multiple timescales data sets was also highlighted in a review paper by (Sun et al., 2018) and attributed to sparsity of observations and interpolation techniques. This highlights the challenges in understanding precipitation variability at interannual and longer timescales.

In the historical period, the observational data sets agree on the spatial patterns of pluvial and drought characteristics (Figures S3 and S4). Duration and average SPI of pluvial and drought events are more spatially

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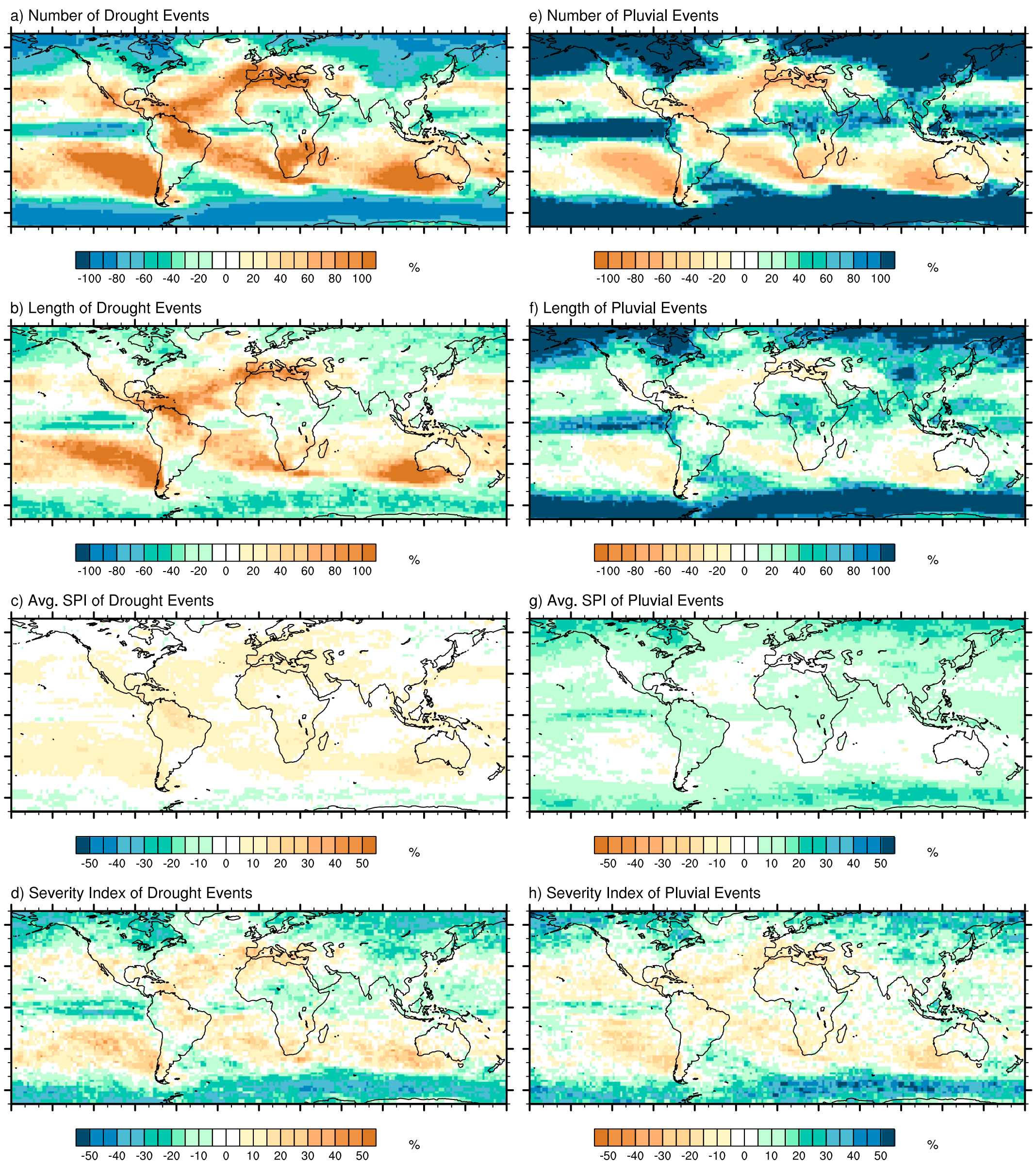

Figure 3. Coupled Model Intercomparison Project Phase 5 multimodel mean percentage changes in drought (left) and pluvial (right) moderate event characteristics: (a and e) number, (b and f) length, (c and g) intensity, and (d and h) severity index. Changes are calculated as future (RCP8.5 2080–2100) to historical (1980–2000). Note the reversed color scales for drought and pluvials characteristics. RCP = representative concentration pathway.

uniform than the number of events, which reflects in the severity index. Regions with the largest variability, as indicated by a high number of pluvial and drought events, extend across the subtropics including southern and eastern Brazil, the Sahel, and India. On average, the longest lasting pluvial and drought occur in northern South America and the horn of Africa (over 4 months for moderate events and 2 to 3 months of severe events). Apart from the deserts of the Sahara, central Asia and the middle East, the average SPI of events is relatively constant across land regions in observations.

There are distinct similarities and differences in the CMIP5 multimodel mean representation of historical pluvial and drought characteristics. The number of pluvial events are underestimated in the models in midlatitudes and drought events are overestimated (by 100% in some locations such as northern North America). The duration and average intensity of events are captured more realistically in the CMIP5 models, but models do miss the enhancement of duration in locations such as northern South America. The regions with largest disagreements between the models and observations are also those with largest disagreements

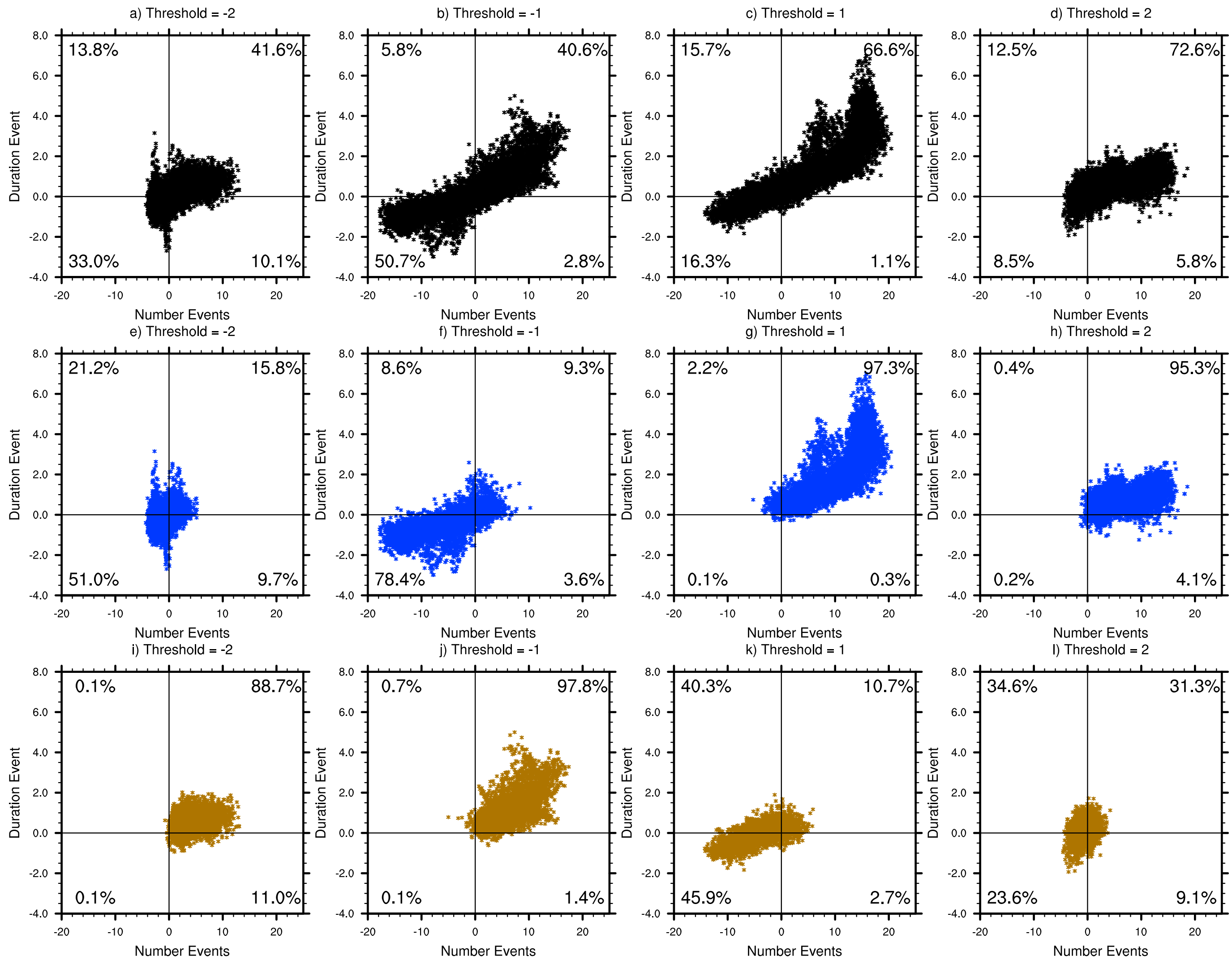

Figure 4. Multimodel mean changes between (RCP8.5 2080–2100) and historical (1980–2000) number and duration of drought/pluvial events at four different thresholds for all grid points (a–d). Each marker indicates an individual grid point. Grid points are isolated for regions with multimodel mean increasing precipitation trends (middle (e)–(h), blue) and decreasing trends (bottom (i)–(l), brown). Numbers indicate fraction of grid points in each quadrant. RCP = representative concentration pathway.

between the two observational data sets in the variability trends (Figure S2). Although the similarities in the spatial distribution of pluvial and drought event characteristics in the CMIP5 models provide confidence in future projections, biases in the magnitudes (especially for number of events) must be considered when interpreting the future projections

3.2. Changes in 21st Century Drought and Pluvial Characteristics

The multimodel mean percentage changes in pluvial and drought event characteristics are shown in Figure 3 for moderate events (Figure S5 for severe events). For moderate events, the number of pluvials are projected to increase by well over 100% in the midlatitudes including across the northern half of North America and most of Asia. The number of drought events is projected to increase by at least 50% across the subtropics, with the largest increases over land in Brazil, surrounding the Mediterranean, and southern Africa. Generally, increases in number of pluvial events are colocated with wetting regions and increases in number of drought events are colocated with drying regions (Figure 1a). Changes in the length of pluvials and droughts follow the same spatial pattern as the changes in number of events. Increased pluvial duration locations include Alaska and interior Asia and drought duration locations include the Caribbean and Mediterranean (increases of approximately 100% or 2–3 months).

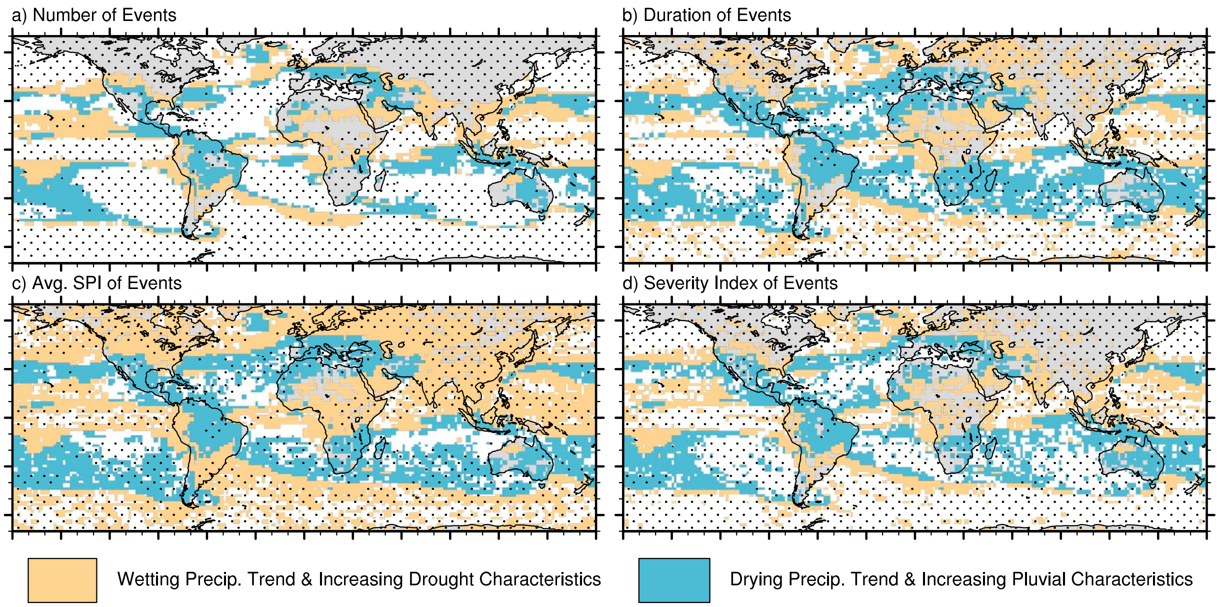

Figure 5. Regions showing opposite precipitation trends and drought/pluvial characteristics occur for (a) number, (b) duration, (c) average SPI, and (d) severity index of severe events for RCP8.5. Stippling indicates regions where at least 18 models agree on the sign of the precipitation trend. SPI = standardized precipitation index; RCP = representative concentration pathway.

The intensity of pluvials and droughts is projected to increase almost uniformly across the globe, irrespective of whether the precipitation is increasing or decreasing, with intensity increasing approximately 10%. Hence, both wet and dry events will likely become more intense in the future, even in regions where the number and/or duration of the events are decreasing. Changing duration and intensity are both captured in the severity index for moderate events, with the maximum increase in pluvial event severity approximately 67%, compared to a maximum increase of 43% for drought severity. Although the pluvial and drought changes almost mirror each other, as expected through of the "rich-get-richer" or "wet-get-wetter" mechanism (e.g., Chou et al., 2009; Trenberth, 2008), there are regions that are projected to experience increases in pluvial and drought characteristics (Table S2). This is most apparent for severe events, where 43% of grid points are projected to see increased duration of pluvials and droughts.

To compare projected changes in event characteristics, Figures 4a–4d show changes in number versus duration for each grid point in the CMIP5 multimodel mean. For pluvial thresholds, the most common quadrant is the upper right, indicating increased number and duration of pluvial events. For severe pluvials, 72% of grid points fall in this quadrant. For the most severe droughts, almost 42% of grid points fall in this quadrant. However, for the moderate drought threshold, the most common quadrant (almost 51% of grid points) is a reduced number and duration of droughts. It is likely that this is because with increased intensity of droughts, they are being "upgraded" from the moderate to severe category, although it is interesting to note that this does not happen on the pluvial side.

To establish whether pluvials and droughts are occurring in conjunction with increasing and decreasing precipitation trends respectively (i.e., rich-get-richer), Figures 4e–4h present the locations only where the multimodel mean precipitation trend is increasing and Figures 4i–4l present the locations only where the multimodel mean precipitation trend is decreasing. For regions where the precipitation trend is increasing (Figures 4g and 4h) the number and duration of pluvial events fall almost exclusively within the upper right quadrant (95–97%) regardless of the severity. The same is seen in locations where the precipitation trend is decreasing (Figures 4i and 4j, 89–98%). However, pluvial events are not exclusively occurring in regions with a wetting trend (and vice versa for droughts), with the largest changes in the most severe events. In locations where precipitation is projected to decrease, over 60% of grid points see severe pluvials that are longer and 40% of grid points see more pluvials (Figure 4l). For severe drought events in regions where precipitation is projected to increase (Figure 4e), over 35% of grid points are projected to see an increase in duration and 25% are projected to see an increase in number of events.

Figure 5 shows regions where changes in pluvial and drought characteristics are in the opposite sense to the precipitation trend in the multimodel mean CMIP5 simulations for the severe events. For example, longer pluvials where the precipitation is projected to decrease. Results for moderate events are consistent and shown in Figure S6. For the number (Figure 5a) and duration (Figure 5b), the signal is predominantly in regions where the model agreement on the sign of the trend is low, across the central United States for example. Increased duration of pluvial events is projected in the Amazon, South Africa, and Mediterranean where models agree on decreasing precipitation in the future. The most spatially extensive signal is for the intensity of events (Figure 5c), where 70% (Table S3) of grid points show this opposite relationship. These results suggest that even in regions where models strongly agree on annual average precipitation decreases in the future (e.g., South Africa, the Southwest United States, and portions of Brazil), severe pluvial event are projected to increase in intensity. The opposite is seen in regions where precipitation is projected to decrease (e.g., northern North America, East Africa, and Asia), where the intensity of severe and moderate drought events are projected to increase.

4. Summary and Conclusions

The ability of historical simulations from 24 coupled ocean-atmosphere global climate models from CMIP5 to simulate number, duration, intensity, and severity of pluvial and drought events has been assessed. Comparing two observational data sets of precipitation (CRU and GPCP) with 24 historical CMIP5 models, agreement is seen in mean precipitation trends in the historical period but there is less agreement (between the two observational data sets and the models) in the variability of precipitation. This highlights challenges with understanding observed precipitation variability. In the regions of disagreement, such as northern North America and central Asia, there is also less certainty in the simulation of pluvial and drought characteristics in the historical period for moderate and severe events. In the future, the variability in the 6-month SPI is projected to increase globally, suggesting that the characteristics of pluvial and drought events will change.

Generally, wet regions are projected to have more frequent, longer lasting, and stronger pluvials (and vice versa for drought events), which is captured by the severity index. However, there are large portions of the globe that will see simultaneous increases in pluvial and drought event severity. As in Findell and Delworth (2010) the Americas stand out for changes in drought characteristics and the Northern hemisphere midlatitudes for pluvials, but significant changes are projected across most of the globe. Especially for the most severe events, locations exist with more, longer, and stronger pluvials despite a decreasing precipitation trend (and vice versa for drought events in regions of overall wetting). Highest confidence is in increased intensity of pluvial events in regions of decreasing precipitation and increased intensity of droughts in regions of increasing precipitation in future projections.

By using SPI to define pluvial and drought event characteristics, we are considering only water supply (i.e., precipitation input). The SPI does not use evaporation or evapotranspiration in its calculation, so capturing the effect of increased temperature in the future is severely limited. Utilizing the standardized precipitation evapotranspiration index (SPEI; Beguería et al., 2014) includes the role of increased temperatures on moisture demand and availability, which is of particular importance for drought events (e.g., Ficklin & Novick, 2017; Novick et al., 2016), but is used less frequently for pluvials. Results using 6-month SPEI, show greater changes in drought characteristics than for SPI, and smaller changes in pluvial characteristics, but overall, the results are supported by SPEI (Figures S9–S11).

This has important implications for planning and resilience to events as changes in the mean precipitation do not provide information about changes in pluvial and drought characteristics. For example, crop and animal agricultural management Rowhani et al. (2011), reservoir storage and dam release Sakho et al. (2017), and human health (Shively, 2017), among others, have all shown to be affected by changing precipitation variability. Changes in drought characteristics are consistent with those from prior studies, but with changes in pluvials at least as large and widespread as changes in droughts, it is necessary to continue to increase mechanistic understanding on the wet side of extended precipitation extremes.

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