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published in
Geophysical Research Letters
2018

DOI (link to publisher)
10.1029/2018GL079439

document version
Publisher's PDF, also known as Version of record

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RESEARCH LETTER

10.1029/2018GL079439

Key Points:
- Significant increases in record-wet and record-dry months are detected in global land observations
- Observed changes indicate a shift in precipitation pattern from lower to higher latitudes in the northern hemisphere
- Changes in rainfall extremes overall reflect changes in monthly-mean rainfall

Supporting Information:
- Supporting Information S1

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Citation:
Lehmann, J., Mempel, F., & Coumou, D. (2018). Increased occurrence of record-wet and record-dry months reflect changes in mean rainfall. *Geophysical Research Letters*, *45*, 13,468–13,476. https://doi.org/10.1029/2018GL079439

Received 2 JUL 2018
Accepted 1 DEC 2018
Accepted article online 13 DEC 2018
Published online 21 DEC 2018

Increased Occurrence of Record-Wet and Record-Dry Months Reflect Changes in Mean Rainfall

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Abstract Climate change alters the hydrological cycle, which is expected to increase the risk of heavy rainfall events and prolonged droughts. Sparse rainfall data, however, have made it difficult to answer the question of whether robust changes can already be seen in the short observational time period. Here we use a comprehensive statistical tool to quantify changes in record-breaking wet and dry months. The global-mean number of record-wet months has significantly increased over the recent decades and is now nearly 20% higher than would be expected in a stationary climate with no long-term trends. This signal primarily comes from pronounced changes in the northern middle to high latitudes where the occurrence of record-wet months has increased by up to 37% regionally. The tropics have seen opposing trends: More record-wet months in Southeast Asia in contrast to more record-dry months in Africa. These changes are broadly consistent with observed trends in mean rainfall.

Plain Language Summary Record-breaking weather events are prominently placed in the media as they are usually associated with severe consequences for the environment and society. Recent examples from 2017 include the record amount of rainfall dumped over Texas by Hurricane Harvey and the unprecedented drought in Cape Town, South Africa. There seems to be an accumulation of such weather extremes over the last decades. However, the question whether this *feeling* stands up to a statistical verification has been challenging to answer. Here we show that there has been a statistically significant increase in the number of record-wet months in the global-mean. This increase is particularly pronounced in Central/East United States, Northern Europe, and Russia, that is, regions which have experienced extreme rainfall events in the recent past leading to severe floods. In contrast, Central Africa has seen an increased occurrence of record-dry months indicating that between 1980 and 2013 roughly one third of all dry-records would not have happened without long-term changes in the climate.

1. Introduction

Changes in monthly precipitation pattern have large impacts on the environment and society. Heavy rainfall events can lead to severe floods, whereas consecutive months of low rainfall can strongly affect the occurrence of droughts (Field et al., 2014). Both can impose severe impacts on agriculture and thus food production. The recent decade has experienced a seemingly large number of extreme rainfall events on both sides—extreme wet and dry months. In 2014, the UK was affected by severe floods (Stephens & Cloke, 2014) and May 2015 was the wettest month ever recorded in the United States with precipitation setting new records over many regions, locally up to 5 times the monthly climatology (National Oceanic and Atmospheric Administration, 2015). This is in line with significant long-term trends of intensifying extreme precipitation and wet spells observed over large parts of the contiguous United States, Europe, and central India (Goswami et al., 2006; Groisman et al., 2005; Hoerling et al., 2016; Zolina et al., 2010). At the same time, significant drying trends have emerged from observations, for example, in parts of Australia and China (Delworth & Zeng, 2014; Zhai et al., 2005). Some subtropical regions have experienced long-lasting droughts including the Middle East, Australia, southwestern United States, and only recently Cape Town in South Africa (Barlow et al., 2015; Heberger, 2011; Kelley et al., 2015). Drought in California led to crop losses and the implementation of an emergency regulation enforcing residents to reduce potable urban water usage by 25% (Wang et al., 2014). Some of these hydrological extremes have been attributed to anthropogenic forcing of the climate (e.g., Hoerling et al., 2012; Kelley et al., 2015; Pall et al., 2011).

Climate change is expected to alter the intensity and frequency of rainfall extremes (Fischer & Knutti, 2015; Min et al., 2011; Pendergrass, 2018). However, the magnitude and sign of change strongly depend on the timescale, season, and location at which rainfall occurs. During the heaviest daily rainfall events, nearly all the moisture in the air is precipitated out and hence those short-lived extremes scale with the water-holding capacity of air which increases by ~7% per degree of warming following the Clausius-Clapeyron (CC) equation. Significant upward trends, in agreement with CC scaling, have been detected in daily precipitation extremes (Berg et al., 2013; Lehmann et al., 2015; Westra et al., 2013). On shorter (sub) hourly timescales extreme precipitation has been observed to increase at about twice the CC rate in some places due to dynamical processes (Lenderink & Fowler, 2017). Global-mean monthly precipitation and evaporation are primarily constrained by the global energy budget and therefore tend to increase at a lower rate of 2–4% per degree warming (Allen & Ingram, 2002). In a warmer climate it will thus take longer for evaporation to moisten the atmosphere toward saturation after an extreme rainfall event, which might lead to prolonged dry periods.

Next to thermodynamics, dynamical effects are also important. Studies point to climate change increasing the intensity of heavy rainfall associated with Hurricane Harvey by far more than expected from the thermodynamic rate of moisture increase indicating that stronger updrafts intensify rainfall from tropical cyclones (Risser & Wehner, 2017; van Oldenborgh et al., 2017; Wang et al., 2018). Moreover, an emerging number of studies indicate that weather (extremes) may become more persistent due to dynamical changes in the atmosphere (Petoukhov et al., 2013; Pfleiderer & Coumou, 2018). Particularly in summer, weakening midlatitude circulation may support stagnant heat extremes with persistent high-pressure systems favoring clear skies and hence suppressing rainfall (Coumou et al., 2015; Lehmann & Coumou, 2015). Also, cyclones may persist locally continuously dumping rain over the same region for days and leading to severe floods as it happened in the Balkans in 2014 (Stadtherr et al., 2016). Consistently, it has been shown that translation speed of tropical cyclones decreased globally by 10% since 1949 increasing local rainfall totals (Kossin, 2018).

Altogether, this might alter the variability of rainfall on monthly timescales. Global-mean monthly precipitation shows a near-zero trend, but pronounced trends are found at the regional level (Sun et al., 2012). Over the twentieth century, monthly mean precipitation increased in the northern middle to high latitudes and in the southern subtropics and tropics while it decreased in the northern subtropics and tropics (Zhang et al., 2007). Tropical land observations indicate a change in the distribution of monthly mean rainfall, with increases in both the driest and wettest months, suggesting a shift toward more extremes (Lintner et al., 2012).

Changes in precipitation extremes, including both prolonged dry and prolonged wet periods, generally impose a stronger impact on society and ecosystems compared to changes in mean rainfall. Here we focus on the most extreme rainfall events, that is, record-breaking events, which often make it to the headlines in the media. However, one may argue that with the *right* choice of the event variables such as time, location, or duration, it is easy to define a rainfall event to be record-breaking. We present a consistent metric to robustly analyze and quantify changes in global and regional record-wet and record-dry months. The observed changes are compared to those expected in a climate with no long-term trends.

2. Data and Methods

2.1. Preprocessing the Precipitation Data

The analysis is based on monthly total rainfall data from the Global Precipitation Climatology Center (GPCC) reanalysis version 7 (Schneider et al., 2015). GPCC is one of the most commonly used products providing consistent and quality controlled rainfall measurements on land covering the time period 1901–2013. The database is derived from nearly 50,000 stations worldwide and interpolated onto a regular longitude × latitude grid with 0.5° × 0.5° spatial resolution. This implies increasing grid cell sizes going from the pole to the equator with typical values on the order of ~40 km in Europe or northern United States and ~55 km in central Africa or Southeast Asia.

Specific data requirements tailored for our study are applied prior to the analysis. To minimize interpolation problems, we only consider those rainfall values from a given grid cell, which have at least one measurement station. All other rainfall values are set to *missing*. This approach is similar but somewhat stricter than in other studies (Simmons et al., 2014; Sun et al., 2012; Tett et al., 2013). Our data requirement removes rainfall observations in South America, Africa, and East Asia during the first half of the twentieth century (see Figure 8 in Becker et al., 2013). Further, rainfall time series with less than 30 years of data or with zero rainfall are excluded from the analysis. The latter requirement is needed for assessing record-dry months since values below zero are precluded, which would prevent the occurrence of any further record-dry month. In leap years, the absolute monthly rainfall value of February is modified by subtracting the mean daily rainfall value of this month from the absolute value. This is necessary in order to compare February values in leap years with February values in other years. Ultimately, we only report results for regions providing at least 100 nonmissing values at each time step.

2.2. Record-Breaking Rainfall Events

A rainfall value (in mm) is defined as a record-wet (dry) month if it exceeds (is lower than) all previous values in the given time series of an individual grid cell. Record statistics have the advantage that no assumption on the underlying probability density distribution is made (Coumou et al., 2013). Record-wet and record-dry months are analyzed for each calendar month individually and then aggregated to annual (including all 12 calendar months) and seasonal averages. Seasons are defined individually for each of the 23 analyzed regions: The choice of regions is based on Field et al. (2012) and then adapted to the specific requirements of our analysis. In particular, we seek regions that are, on the one hand, large enough to yield robust statistics, for example, by maximizing the signal-to-noise ratio, but on the other, small enough so that important region-to-region variation is preserved. The region's wet season is defined as those five consecutive calendar months, which show the highest regional-mean rainfall over the full climatology (1901–2013). Similarly, those five consecutive months showing the least amount of rainfall were chosen for the region's dry season. The same definition for wet and dry seasons is hence used for all grid cells within the same region, which is a good approximation especially for regions with pronounced seasonality (Figure S1 in the supporting information). Reducing the season length to 3 months leads to similar results with all conclusions presented here remaining valid (not shown).

2.3. Calculating the Record-Anomaly

To assess how climate change affects the occurrence and frequency of record-rainfall events, the number of observed record-rainfall events is compared to that expected in a stationary climate with no long-term changes. As in Lehmann et al. (2015), we assume that in a stationary climate rainfall observations can be described as independent and identically distributed for which the number of expected record-events after N time steps steps is $R_N = \sum_{n=1}^{N} 1/n$. We define the record-anomaly as

$$R_{\mathrm{anom},i} = \frac{R_{\mathrm{obs},i} - R_{N,i}}{R_{N,i}} \cdot 100(\%),$$

which describes how much the observed number of record-events (R_{obs}) at grid point i deviates from that expected in a climate with no long-term trends (R_N). Regional aggregates of record-anomalies are calculated using

$$R_{\mathrm{anom},R} = \frac{\sum_i w_i R_{\mathrm{obs},i} - \sum_i w_i R_{N,i}}{\sum_i w_i R_{N,i}} \cdot 100(\%),$$

with the sum including all grid points i in region R and w_i denoting the area-weighting factor to account for different grid cell sizes. Each monthly rainfall time series of a given grid cell is compared to its individual $1/n$ time series, thus accounting for missing values and any spatial and temporal inhomogeneities in the observations. For temporal averages all (expected) records in the considered time period are summed up in the above formula.

Long-term nonlinear trends in the record-anomaly time series are calculated using Singular Spectrum Analysis (Allen, 1997; Golyandina et al., 2001). This method uses eigenvalue decomposition to filter out nonlinear trends from white noise. The chosen window length of 15 years gives similar results as a 30-year moving average but avoids losing the first and last 15 years of the time series.

2.4. Regional Permutation Tests to Determine Significance

Statistical significance is determined using the shuffling method as described in detail in Lehmann et al. (2015). Accordingly, each time series is shuffled 10,000 times—in which process any trend, change in variance, and autocorrelation are removed—to create a set of iid time series under the null hypothesis of a stationary climate. The method takes care of spatial correlation within a given region by using the same resampling order for all shuffled time series available for this region. This way, possible changes over time

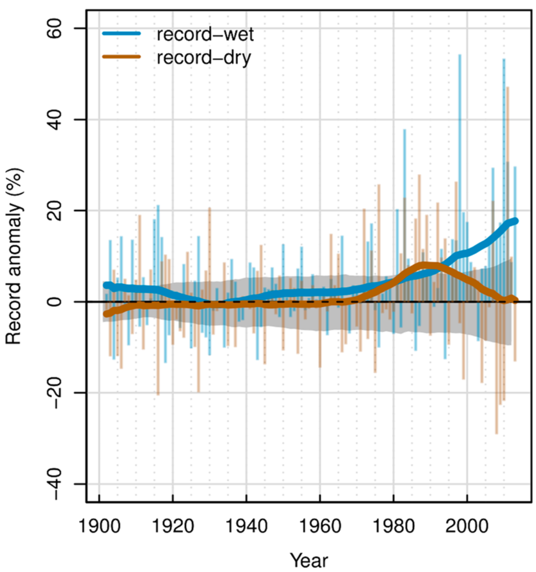

Figure 1. Global change in record-breaking rainfall events. Record-wet (blue vertical bars) and record-dry (brown vertical bars) anomalies and their long-term nonlinear trend based on singular spectrum analysis (solid lines) are shown. Both long-term trends show periods of significant increases as indicated by exceeding the 95% confidence interval of the long-term changes of the stationary model (grey shaded area).

such as increasing or decreasing trends in regional data coverage are lost, which, however, only has minor effects on the analysis (Lehmann et al., 2015). We define the observed record-anomaly to be statistically significant if it is outside of the 95% confidence range, which is computed from the distribution of sampled record-anomalies based on the shuffled time series. When assessing multiple regional significance tests, we additionally apply Benjamini-Hochberg false discovery rate (FDR) correction to the regional results to account for the increase of false positives due to multiple testing (Benjamini & Hochberg, 1995). Given the spatial correlation of the fields, we use $\alpha_{FDR} = 2 * 0.05$ to get a global α level of 0.05 (Wilks, 2016).

2.5. Calculating Trends in Mean Precipitation

We use a τ-based Mann-Kendall test to examine the direction of change in monthly precipitation time series (Chandler & Scott, 2011; Westra et al., 2013). This method does not make any assumption on the underlying distribution of the data or on the particular form of the trend. The Mann-Kendall parameter τ statistically assesses whether there is an upward or downward trend in the given data with a positive value implying that observations later in the time series tend to be larger than earlier observations and vice versa for negative τ values. The parameter τ can be as high as 1 in which case the time series is monotonically increasing or as low as -1 in case of a monotonically decreasing time series. We calculate τ for each calendar month and grid point and then average over the same regions and seasons as for the analysis of the record-anomaly. The calculated regional averaged Mann-Kendall (RAMK) parameter is similar to the one described in Renard et al. (2008) with the only difference that we calculate area-weighted averages. We test whether the observed trends are statistically different from the null hypothesis of no trends using the same shuffling method as described above. Hence, a distribution of 10,000 shuffled time series is created from which the 95% confidence range is extracted to define statistically significant trends in the observations.

3. Results

On the global scale, the annual record-wet anomaly has significantly increased since the 1980s (Figure 1). The long-term trend (thick blue line) reaches a value of 18% in 2013 indicating that approximately one out of six observed record-wet months cannot be explained without taking long-term climate changes into account. The record-dry anomaly stays within the uncertainty range of the stationary climate (grey background shading) for most of the time. However, during the 1980s and 1990s, a significant increase in record-dry months can be observed with a peak value of 8%. This signal primarily comes from contributions during the wet season and is related to a series of record-dry years starting in the early 1980s (Figure S2).

Three years stick out with exceptionally many wet-records: 1983, 1998, and 2010. The increases in 1983 and 1998 are more pronounced in the dry season, whereas the increase in 2010 is only evident in the wet season (Figure S2). Based on the given data set, the year 2010 was indeed the wettest year on record in terms of global land-mean rainfall, whereas 1983 and1998 only come in at 84th place and19th place, respectively. The latter 2 years, however, are among the most extreme El Niño years in the observational period, causing a massive disruption of the atmospheric circulation, which resulted in many rainfall records (Capotondi et al., 2015; Takahashi et al., 2011). The three example years illustrate that a year with many record-wet months does not necessarily imply that it was also a very wet year in terms of total precipitation.

The global increase in record-wet months during the time period 1980–2013 is primarily a northern hemisphere midlatitude to high-latitude signal (Figure 2). Slicing the global land area into seven zonal bands, we find that the northern middle to high latitudes have experienced the strongest increases (up to 28%) in record-wet months. The tropics have seen a significant increase in record-dry months of around 21–27%. The observed changes in record-anomalies are in general agreement with zonally averaged Mann-Kendall (RAMK) trends of monthly precipitation (calculated at the grid level), indicating a drying of the tropics and

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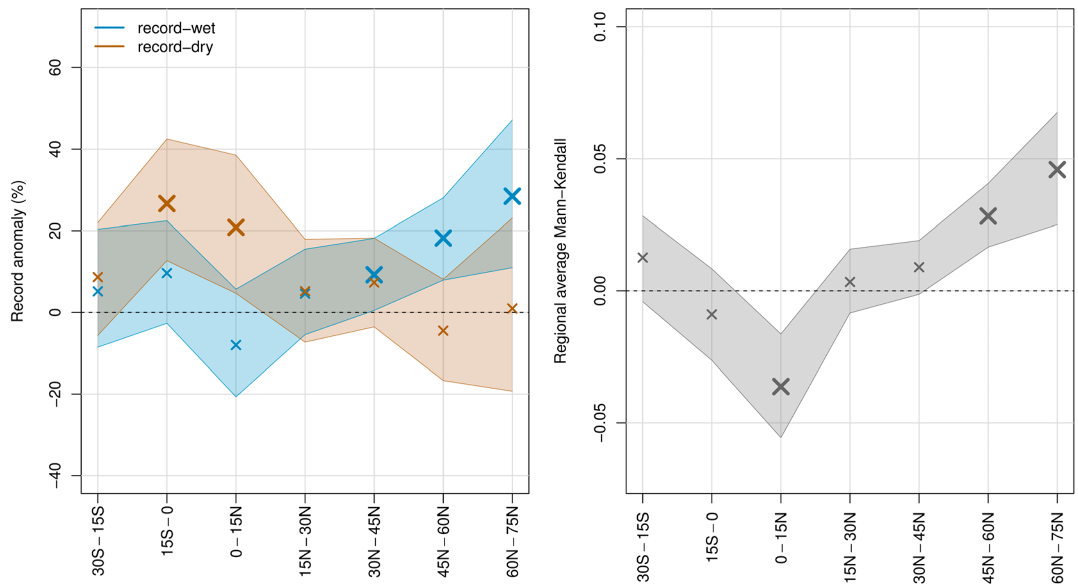

Figure 2. Zonal-mean changes in record-rainfall events (1980–2013) and mean rainfall trends. (left) Record-wet (blue) and record-dry anomalies (brown) show different significant changes depending on the latitude. (right) Mann-Kendall trends of monthly rainfall indicate a shift from the tropics toward the northern high latitudes. In both figures, observations are marked with crosses and the 95% confidence range is indicated by colored shading.

wetting of the northern middle to high latitudes. This signal appears to be consistent throughout the year and independent of the season (Figures S3 and S4). Note that record-anomalies averaged over the time period 1980–2013 still account for all rainfall measurements before 1980 since the occurrence of a record

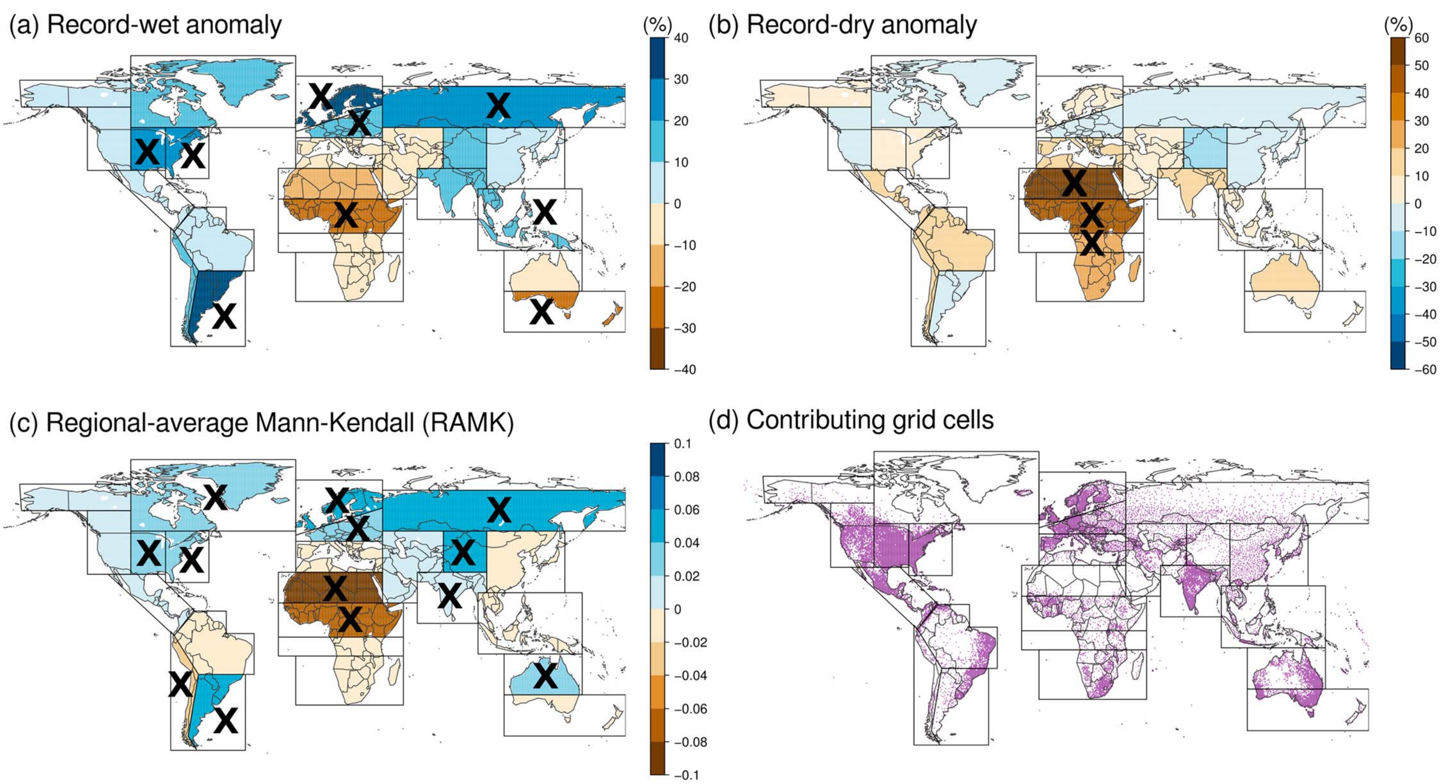

Figure 3. Global maps of regional-mean changes in record rainfall events (1980–2013) and mean rainfall trends. Changes in (a) record-wet and (b) record-dry anomalies are fairly consistent with trends in mean rainfall computed from (c) RAMK. Significant changes at a global 5% level are marked with a black cross. Grid cells, which contribute rainfall measurements to the analysis, are indicated by purple color (d).

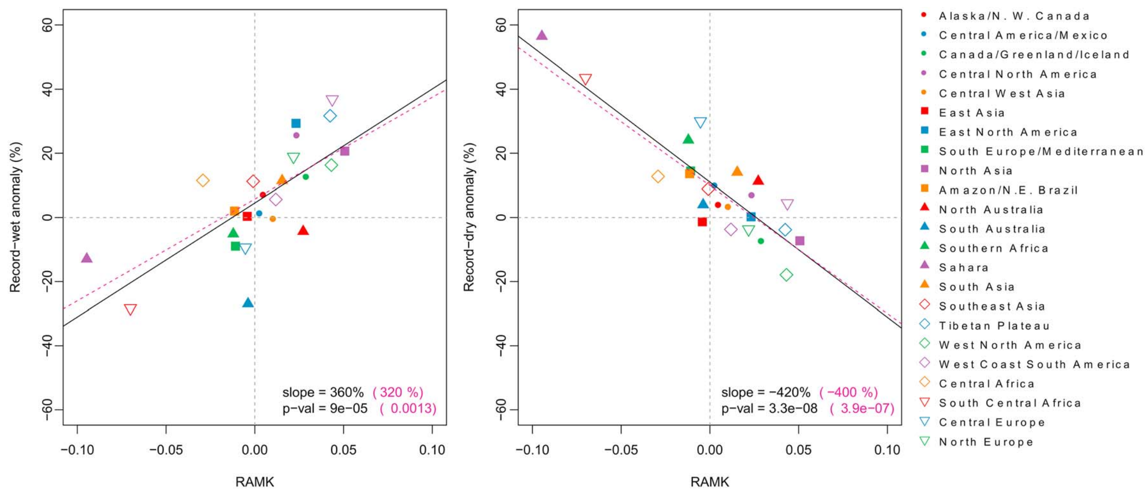

Figure 4. Relationship between regional-mean Mann-Kendall trends and record-anomalies (1980–2013). The relationship with (left) record-wet and (right) record-dry anomalies is shown. The solid black lines show the linear fit with slope and *p*-values given at the bottom of each panel. The dashed purple line indicates the linear fit when leaving out the extreme values for Sahara and South Central Africa.

event is based on all previous values. Thus, record-anomalies presented here are compared to RAMK calculated for the full time period available.

The northern midlatitude to high-latitude wetting (see Figure 3) primarily comes from a regionally uniform signal with significantly increased record-wet anomalies in central and eastern United States (26% and 29%, respectively), central and northern Europe (19% and 37%), and northern Asia (21%). Significant regional increases are also detected for South East Asia (11%) and southern South America (32%). However, regions with significantly fewer record-wet months are also found at these latitudes, that is, in Central Africa (−28%) and southern Australia (−27%). The pronounced drying signal in the tropical belt comes from (South) Central Africa and the Sahara region (including the Sahel zone) where record-dry months have increased by 30%, 44%, and 56%, respectively. Well-documented extreme drought years in these regions in 1972–1973 and 1983–1984 are associated with high occurrence of record-dry months (Figure S5; Masih et al., 2014). A significant 48% increase in record-dry anomaly can also be observed in southern Africa during the dry season where extreme droughts in 1948–1949 and 1991–1992 led to an exceptional high number of dry records (Figures S7–S9).

Significant changes in regional record-anomalies are well aligned with significant changes in mean rainfall trends. This means that observed increases in record-wet months are associated with positive RAMKs, that is, upward trends in mean rainfall, and increasing record-dry anomalies are associated with negative RAMKs. The only exceptions are Southeast Asia and South Central Africa where significant changes in record-anomalies are not aligned with significant RAMK trends. In turn, there are two regions where only RAMK shows significant results: the region including northern Canada/Greenland/Iceland and the Tibetan Plateau where low signal-to-noise ratio hampers the detection of significant record-wet anomalies. It should be noted that regional aggregates are calculated from only those grid cells that are colored in Figure 3d.

Regression analysis of regional trends and changes in record-anomalies reveals a significant linear relationship for both record-wet and record-dry months (Figure 4). Thus, the stronger the Mann-Kendall trends, the more record-wet or record-dry months—depending on the sign of the trend—can be observed. The relationship is robust and of similar magnitude when separating between wet and dry season (Figures S9 and S10). Moreover, the same relationship with comparable slopes is found if trends and record-anomalies computed at the grid level are regressed (not shown) or if extreme values from the Sahara and South Central Africa are excluded from the regression (see purple line, Figure 4).

4. Conclusions

Record-breaking rainfall events often receive a disproportional amount of attention from the media. Theory based on fundamental physical laws as well as regional case studies suggest an increasing frequency of monthly rainfall records, but as yet this has not been shown in a coherent global study.

Here we report significant changes in the occurrence of observed record-breaking wet and dry months in global land observations. These changes have distinct regional patterns and are generally consistent with computed trends in monthly mean rainfall. The middle to high latitudes in the northern hemisphere have seen a strong wetting trend and associated increases in wet-records. The tropics, on the other hand, are characterized by a significant increase in record-dry months over Central Africa but an increase in record-wet months over Southeast Asia.

The presented changes in record-breaking rainfall are consistent with trends in extreme precipitation found by previous studies using different extreme measures. First of all, the overall increase in record-breaking wet months is in line with different globally aggregated extreme precipitation indices showing a tendency toward wetter conditions throughout the twentieth century (Alexander et al., 2006). Moreover, regional studies found significant increases in different classes of heavy daily rainfall over Canada and the contiguous United States (Groisman et al., 2005; Hoerling et al., 2016; Kunkel et al., 1999). Similar to our results these increases are most notable in the eastern two thirds of the country. Increases in observed extreme precipitation have also been reported in Europe and associated with longer and intensified wet spells (Groisman et al., 2005; Madsen et al., 2014). In other words, there are indications that over Europe short-lived rainfall events have regrouped into prolonged wet spells lasting for 3–4 days or longer (Zolina et al., 2010), which may explain why we find a similar pattern also at monthly timescales. It should be noted that at a given location precipitation extremes may exhibit very different trends depending on the rainfall duration considered (Zheng et al., 2015). Hence, conclusions drawn from trend comparisons of different rainfall durations or extreme metrics need to be treated with caution.

In the tropics, we find contrasting changes in rainfall extremes between Africa and Southeast Asia. In the former region, record-dry months increased by up to 56% in 1980–2013 implying that approximately one out of three record-dry months would not have occurred without long-term climate change. In southern Africa this may be linked to observed increasing trends in consecutive dry days (Donat et al., 2013). We would like to note that time series with zero rainfall were removed from the analysis, and thus, we are not able to make statements about changes in record-dry months in the driest regions. Analyzing record-dry *seasons* would overcome this limitation but at the same time would have different implications and processes involved that are outside the scope of this study.

Overall, our results suggest that for most regions the detected changes in record anomalies are related to trends in mean rainfall. In fact, we find a significant linear relationship between both record-wet and record-dry anomalies and respective Mann-Kendall trends. This is consistent with the theoretically expected number of records scaling linearly with the trend in the mean when changes in variability are assumed to be zero. This linear scaling of record-breaking events is fundamentally different from the nonlinear behavior of threshold exceeding extremes (see Figure 2 in Rahmstorf & Coumou, 2011). Of course, a positive Mann-Kendall trend is not necessarily linear, but our results suggest that this relationship still holds.

Whereas some regions are thus facing the risk of prolonged dry periods, the reported wetting of northern midlatitude to high-latitude winter months favors the occurrence of floods. The observed increase in the number of record-wet months is especially pronounced over central and eastern United States, Europe, and Russia showing annual increases ranging between 19% and 37%. These regions are strongly affected by extratropical storm tracks and have experienced extreme rainfall events in the recent past leading to severe floods. Climate change will likely continue to alter the occurrence of record-breaking wet and dry months in the future under increasing CO_2 emissions with severe consequences for agricultural production and food security.

Acknowledgments
We thank the Global Precipitation Climatology Centre for making their data available. For this study, GPCC data were retrieved from the website of the German Weather Service (ftp://ftp.dwd.de/pub/data/gpcc/html/fulldata_v7_doi_download.html). The work was supported by the German Research Foundation (CO994/2-1) and the German Federal Ministry of Education and Research (01LN1304A).

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