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Historical Changes in Global Extreme Precipitation in Climate Models and Observations

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Abstract

Precipitation events are expected to become substantially more intense under global warming, but few global comparisons of observations and climate model simulations are available to constrain predictions of future changes in precipitation extremes. We present a systematic global-scale comparison of changes in historical (1901-2010) annual-maximum daily precipitation between station observations (compiled in HadEX2) and the suite of global climate models contributing to the fifth phase of the Coupled Model Inter-comparison Project (CMIP5). We use both parametric and non-parametric methods to quantify the strength of trends in extreme precipitation in observations and models, taking care to spatially and temporally sample them in comparable ways. We find that both observations and models show generally increasing trends in extreme precipitation since 1901, with largest changes in deep tropics. Annual-maximum daily precipitation has increased faster in the observations than in most of the CMIP5 models. On global scale, the observational annual-maximum daily precipitation has increased by an average of 5.73 mm over the last 110 years or 8.5% in relative terms, corresponding to an increase of 10% per K of global warming since 1901, which is larger than the average of climate models with 8.3%/K. The average rate of increase in extreme precipitation per K of warming in both models and observations is higher than the rate of increase in atmospheric water vapor content per K of warming expected from the Clausius-Clapeyron equation. We expect our findings to help inform assessments of precipitation-related hazards such as flooding, droughts and storms.

Introduction

Anthropogenic climate change is expected to change the distribution, frequency and intensity of precipitation and result in increased intensity and frequency of floods and droughts, with damaging effects on environment and society.

As a result of global warming, climate models and satellite observations both indicate that atmospheric water vapor content has increased at a rate of approximately 7% per K warming, as expected from the Clausius-Clapeyron equation under stable relative humidity. Increasing availability of moisture in the atmosphere can be expected to result in increased intensity of extreme precipitation, with proportionally greater impact than for mean precipitation.

Although climate models generally indicate an increase in precipitation and its extremes, the rate of this increase seems to be underestimated, which implies that future projections of changes in precipitation extremes may also be under-predicted. Assessments of climate models also reveal that the rate of increase in precipitation extremes varies greatly among models, especially in tropical zones, which makes it especially important to compare modelled trends with those identified in observations. However few global comparisons of observations and climate model simulations are available to constrain predictions of future changes in precipitation extremes.

Methodology

The extreme precipitation index here is defined as the annual-maximum daily precipitation, in which the maximum one day precipitation (Rx1day) amount is selected for each year.

Climate models and observation datasets do not provide the same spatial and temporal coverage for precipitation data, leading to some uncertainties in the comparison of the results. In the present study, precipitation data for years/grids of climate models which do not have corresponding observational data are excluded, resulting in a comparable sampling approach for both datasets.

We chose to use only the grid-cells with at least 30 years of available precipitation data over the last 110 years, which includes more than 90% of the 766 HadEX2 data grid-cells.

Tests for the trend detection in climatologic time series can be classified as parametric and non-parametric methods. Parametric trend tests require independence and a particular distribution in the data, while non-parametric trend tests require only that the data be independent. The trend slope (b) obtained from the linear regression method which assumes that the data availability follows a normal distribution is utilized for trend strength analysis and comparison of the datasets. Similar to the linear regression slope (b), Qmed from the Sen’s test shows the direction and magnitude of the trend in the time series, having the advantage of using a non-parametric method for trend test.

The change in extreme precipitation per K of warming is also calculated as an index for the relation between changes in precipitation extremes of each grid-cell with global mean near-surface temperature, which indicates the percentage of change in extreme precipitation per K global warming.

The Z-score (Z) obtained from the Mann-Kendall test and Q-median (Qmed) from the Sen’s slope estimator are applied in order to support the results of linear regression, using non-parametric trend detection approaches.

Results and Discussion

Linear regression indicates that 66.2% of the studied grid-cells show a positive trend in annual-maximum daily precipitation during the past 110 years, including 18% that are statistically significant at 95 percent confidence level. On the other hand, 33.8% of the studied grids show a negative trend including only 4% that are statistically significant at 95 percent confidence level.

The global average of extreme precipitation data shows higher value than the largest value obtained from the climate models, which indicates that all of the climate models underestimate the RX1day. This underestimation can be seen on continental scales as well, and is expected given the difference in spatial scale between GCMs and station precipitation gauges (Table 1 and Fig. 1.a.).

Table 1. Statistics of variation of global extreme precipitation for HadEX2 and the 19 Subsampled CMIP5 model runs from 1901 to 2010. The table presents the statistics for the global average of the parameters. The 19 Climate model runs give 19 global averages of which the minimum, maximum, median, mean and standard deviations are presented.

		Q_{med} (mm.day^{-1}.year^{-1})	Z – score (-)	Slope of Change (b) (mm.day^{-1}.year^{-1})	Average of extreme precipitation (P) (mm.day^{-1})	Relative change (b/ P) (% . year^{-1})	Change per degree warming (%/K)
CMIP5 (Subsampled)	Model Min	0.0005	0.0944	0.0023	29.31	0.0118	4.37
	Model Max	0.0648	0.7050	0.1592	48.46	0.3849	28.67
	Model Median	0.0218	0.3056	0.0271	37.89	0.0606	7.3
	Model St. Deviation	0.0133	0.1555	0.0326	5.08	0.0774	5.16
	Model Average	0.0230	0.3330	0.0314	37.85	0.0797	8.43
HadEX2	-	0.0504	0.7242	0.0521	55.03	0.0775	9.99

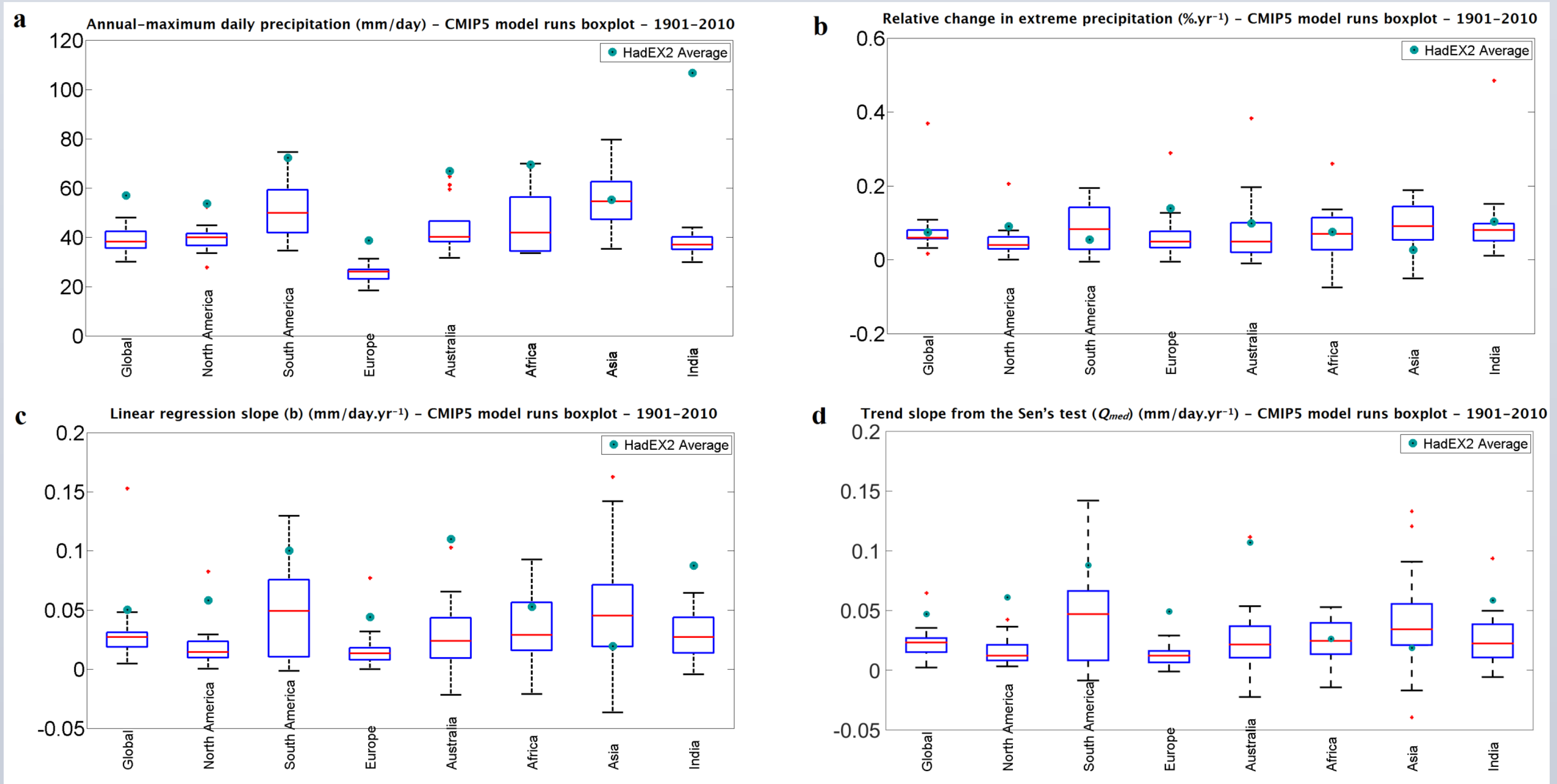

Figure 1. Boxplots of CMIP5 model run averaged results (minimum, 25th percentile, median, 75th percentile and maximum of the 19 model runs) as well as average of HadEX2 observational data (shown as blue circles) for 1901–2010 extreme precipitation data in global and continental scale” - Annual-averaged daily extreme precipitation [mm.day-1] (a), relative change in annual-averaged daily extreme precipitation (%.year-1) (b), linear regression slope of change in annual-averaged daily extreme precipitation (mm.day-1.year-1) (c) and trend slope from the Sen’s test (Qmed) (mm.day-1.year-1) (d). The red markers outside the boxes represent the outliers.

Results show that both observations and climate models show generally increasing trends in extreme precipitation intensity since 1901 (Table 1). Although the climate models reproduce the direction of observational trends on global and continental scales, the rate of change seems to be underestimated in models though the observations fall within the range of inter-model variability at least for the global mean relative change (b/P). Similar discrepancies between observations and climate models have also been reported in earlier studies.

The global average of trends from the non-parametric method (Qmed from Sen’s slope estimator) show similar values to those obtained from the parametric method (b from the linear regression) in observations, confirming the results of the parametric method, which further supports increasing trend in observational annual-maximum daily precipitation (Table 1 and Fig. 1.c and d). Also the boxplots of b and Qmed for climate models are very similar on global and continental scale for different percentiles (Fig 1.c and d, respectively).

Tropical latitudes show higher ranges of fluctuations observed and simulated for extreme precipitation trends compared to mid-latitudes, as well as larger discrepancy between the observations and simulations. The continents of North America, Europe and Asia contain about 22, 18 and 34 percent of total global data grid-cells. The trend results averaged for the continents of North America and Europe are generally in line with global averaged results.

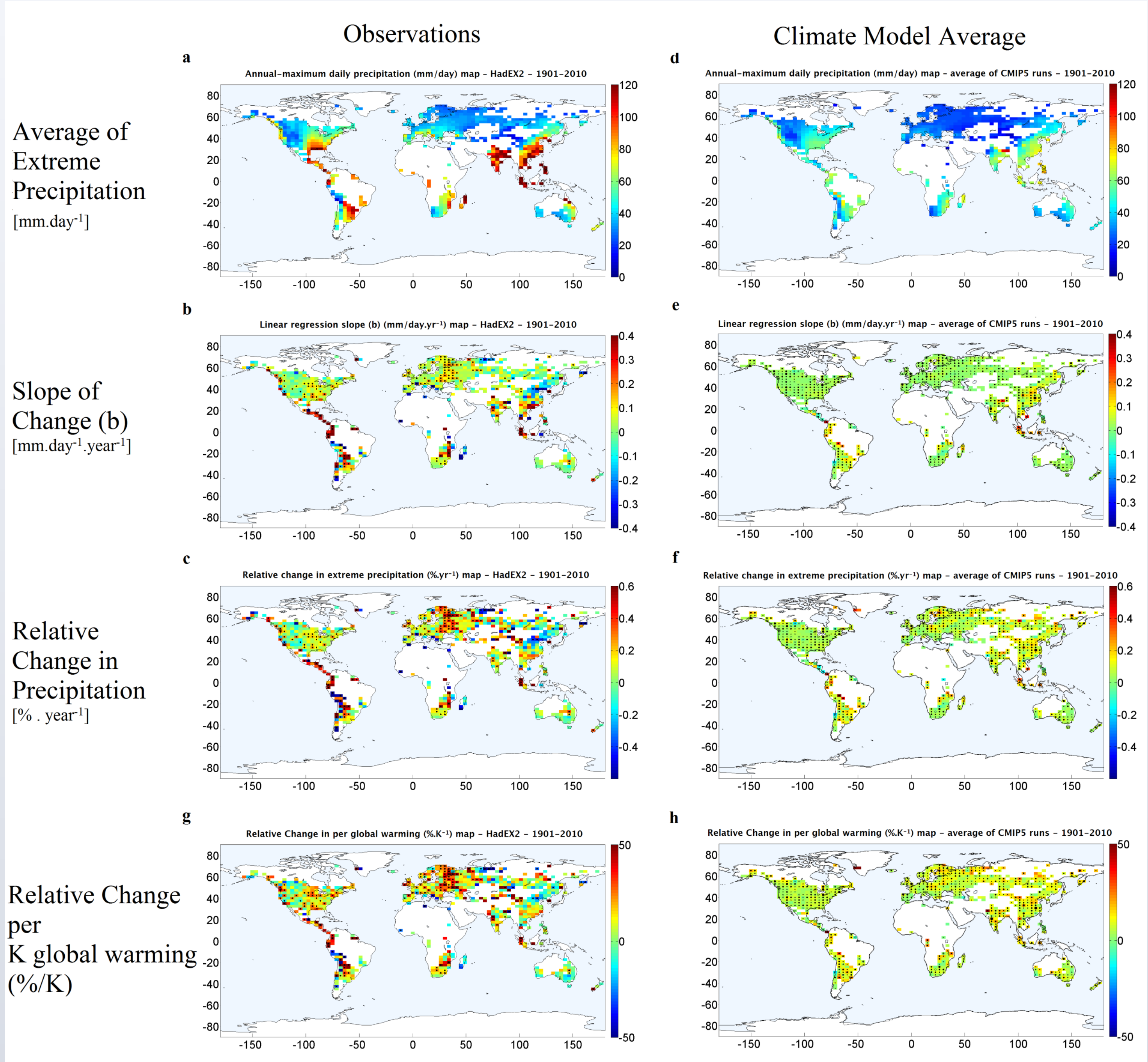

Figure 2. HadEX2 observational data versus CMIP5 averaged results of global extreme precipitation data 1901-2010 - Annual-averaged daily extreme precipitation map (mm.day-1) for HadEX2 (a) and average CMIP5 (d), Slope of change in annual-averaged daily extreme precipitation map (mm.day-1.year-1) for HadEX2 (b) and average CMIP5 (e), relative change in annual-averaged daily extreme precipitation (%.year-1) map for HadEX2 (c) and average CMIP5 (f) and relative change in extreme precipitation per K of global warming (%/K) map for HadEX2 (g) and average CMIP5 (h) . Stippling inside the grids indicates significance of calculated trend at 95% confidence level.

The Clausius-Clapeyron equation indicates that atmospheric water vapor content increases at a rate of 7% per K of warming. Although change in global-mean precipitation with respect to warming does not scale with the Clausius-Clapeyron equation and from energy balance consideration the rate of increase might be expected to be around 2%/ K, impact of global warming on extreme precipitation is expected to be stronger. The results of the present study show that on average, extreme precipitation since 1901 has increased by 10% per K of global warming in observations and 8.3%/K in climate models over land areas with station observations available (Table 1). North and South America as well as Europe show even stronger increase in extreme precipitation with respect to global warming (Fig. 2g and h). These numbers are considerably larger than the 7%/K of the Clausius-Clapeyron equation, which further emphasizes the impact of changes in the Earth’s global temperature on precipitation extremes.

Conclusion

Faster change in extreme precipitation than mean precipitation implies a change in precipitation pattern, where the climate shifts to fewer rainy days and more intense precipitation. This can affect the availability of fresh water resources throughout the year. Such changes in precipitation pattern can affect the capability of reservoirs to capture excessive surface run-off and result in increased flooding events. Failure of the available reservoirs to capture the designed amounts the annual surface run-off might also result in less total annual amount of water stored in the reservoir, hence less available fresh water resources. Design of newly constructed reservoirs strongly depends on the appropriate prediction of future climate and precipitation extremes, but the available climate models seem to underestimate those for at least some regions.

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