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How much do precipitation extremes change in a warming climate?

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[1] Daily data from reanalyses of the European Centre for Medium-Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction (NCEP) are analyzed to study changes in precipitation intensity with respect to global mean temperature. The results are in good agreement with those derived from the Global Precipitation Climatology Project (GPCP) data by Liu et al. (2009), providing an independent verification for large changes in the precipitation extremes: about 100% increase for the annual top 10% heavy precipitation and about 20% decrease for the light and moderate precipitation for one degree warming in the global temperature. These changes can substantially increase the risk of floods as well as droughts, thus severely affecting the global ecosystems. Atmospheric models used in the reanalysis mode, with the benefit of observed wind and moisture fields, appear to be capable of realistically simulating the change of precipitation intensity with global temperature. In comparison, coupled climate models are capable of simulating the shape of the change in precipitation intensity, but underestimate the magnitude of the change by about one order of magnitude. The most likely reason of the underestimation is that the typical spatial resolution of climate models is too coarse to resolve atmospheric convection.

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1. Introduction

[2] Changes in precipitation extremes are of great importance to the welfare of human beings as well as the entire ecosystem. Increases in heavy precipitation can increase surface runoff and lead to more and worse floods and mudslides. On the other hand, decreases of light and moderate precipitation can lengthen dry spells and increase the risk of drought because light and moderate precipitation is a critical source of soil moisture as well as ground water.

[3] Significant increases of the very heavy precipitation and decreases of light and moderate precipitation have been reported using historical rain gauge data over many land areas [*Karl and Knight*, 1998; *Manton et al.*, 2001; *Klein Tank and Können*, 2003; *Liu et al.*, 2005; *Fujibe et al.*, 2005; *Groisman et al.*, 2005; *Goswami et al.*, 2006; *Lenderink and Meijgaard*, 2008]. Over the oceans, analyses of satellite data from 1979–2003 at low latitudes (30°S–30°N) also found similar changes [*Lau and Wu*, 2007]. The widespread increases of heavy precipitation have been attributed to global warming [*Trenberth*, 1998; *Semenov and Bengtsson*, 2002; *Allen and Ingram*, 2002; *Trenberth et al.*, 2003]. *Trenberth et al.* [2003] hypothesized that the precipitation intensity should increase at about the same rate as atmospheric moisture which increases at about 7% K^{-1} according to the Clausius-Clapeyron equation. They argued that the increase in heavy rainfall could even exceed the 7% K^{-1} because additional latent heat released from the increased water vapor could invigorate the storms. However, they didn't give any quantitative estimate how much over the Clausius-Clapeyron rate or at what intensity of the storms.

[4] An invigorated storm could remove moisture by more than 7% K^{-1} from the atmosphere. On the other hand, global evaporation, which is determined by global surface energy budget, increases at the same rate as global-mean precipitation, about 2–3% K^{-1} [*Cubasch et al.*, 2001]. This means that in a warmer climate it would take longer for evaporation to replenish atmospheric moisture, thus longer dry spells between storms. Moreover, the enhanced latent heating from convection would make the atmosphere more stable and thus less likely to precipitate, especially for light and moderate precipitation that requires an unstable large-scale environment. The combined effect is to increase the intensity of heavy precipitation from large storms while suppressing light and moderate precipitation.

[5] These thermodynamic arguments are broadly confirmed by an analysis of model-simulated changes by *Sun et al.* [2007] and an analysis of observational data by *Liu et al.* [2009], who examined inter-annual variations of observed precipitation from the GPCP [*Huffman et al.*, 2001; *Xie et al.*, 2003]. Both studies find increases in very heavy rainfall exceeding the 7% K^{-1} (bin 10 of Figure 1), and decreases in moderate precipitation (bins 2 to 5 of Figure 1). In fact, the two studies agree very well in the shape but differ by about one order of magnitude. The analysis of daily data from 14 coupled global climate models (GCMs) by *Sun et al.* [2007] showed that, under global warming conditions driven by increasing greenhouse gases, the increase of global-mean precipitation intensity (see auxiliary material for definition of precipitation intensity) could be calculated by averaging the increase in precipitation intensity at each grid point.[1] They obtained an increase of global-mean precipitation intensity of about 2.2% K^{-1} for the multi-model ensemble average, with a relatively small scattering of 1.4–3.3% K^{-1} among the

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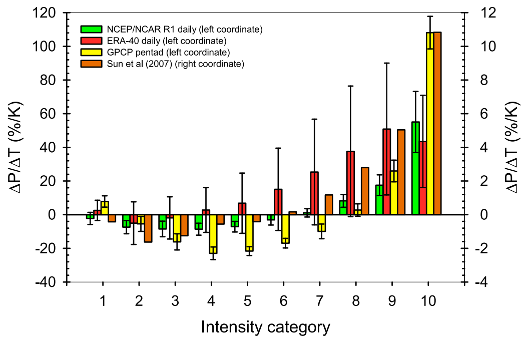

Figure 1. Changes in the precipitation amount falling within each of the ten intensity bins (ΔP, expressed in % of the average precipitation amount of each bin over the time period of data) for one degree increase in global temperature (ΔT). Yellow bars denote the ΔP/ΔT values derived from the GPCP pentad data in 1979–2007. Brown bars are the ΔP/ΔT values derived from an ensemble of 14 climate models as reported by *Sun et al.* [2007]. Green and red bars are those from NCEP/NCAR R1 and ECMWF ERA40 reanalyses, respectively. The vertical line on top of each bar denotes the ±1-standard deviation range.

models [see *Sun et al.*, 2007, Table 2]. This intensity increase is significantly higher for top 10% or heavier precipitation, at a rate exceeding the 7% K^{-1} (Figure 1), in agreement with the hypothesis of *Trenberth et al.* [2003]. Nevertheless, the mean intensity increase in the model-simulated long-term changes is about one order of magnitude smaller than that derived from the inter-annual variations in the GPCP pentad data [*Liu et al.*, 2009]. Underestimates by climate models for the increase in very heavy precipitation in response to increases of sea-surface temperatures (SST) by a factor of about two over the tropical oceans were noticed by *Allan and Soden* [2008]. Model-simulated changes in heavy precipitation were also found to be smaller than those seen in limited daily rain gauge data over many Northern Hemisphere land areas [*Min et al.*, 2011].

[6] This underestimation of changes in heavy precipitation by climate models are not unexpected given that current GCMs tend to produce too much light and moderate precipitation while missing most heavy and extreme precipitation events [*Dai and Trenberth*, 2004; *Dai*, 2006; *Sun et al.*, 2006]. This large bias results mainly from difficulties in representing small scale (∼1–10 km) atmospheric convection in GCMs with a grid size of 100 km or more. Specifically, moist convection tends to start prematurely in most GCMs, leading to weak but frequent convections, an incorrect diurnal cycle, and too much convective precipitation and too little stratiform precipitation in most GCMs [*Dai and Trenberth*, 2004; *Dai*, 2006].

[7] Although there are significant differences in data resolution and analysis methods between *Sun et al.* [2007] and *Liu et al.* [2009], the large difference in the changes for different precipitation categories between the models and GPCP data still raises a serious concern that the risk of extreme precipitation events under global warming, including floods and droughts, may be substantially greater than that estimated by climate models as of 2007. This further illustrates the importance of realistic representation of moist convection in GCMs, as it not only has a major impact on atmospheric vertical transport of heat, water vapor and the formation of clouds, thus affects tropospheric and surface energy budgets, but also affects extreme weather events, such as heavy precipitation, floods and droughts.

2. Concerns About the GPCP Data

[8] Besides the well-known model deficiencies in simulating convection that could lead to models' underestimation of heavy precipitation changes under global warming conditions, there are other aspects that could contribute to the large difference between the results of *Sun et al.* [2007] and *Liu et al.* [2009]. For example, *Sun et al.* [2007] examined long-term changes induced by increases in greenhouse gases, while *Liu et al.* [2009] analyzed inter-annual variations (hereafter referred to as inter-annual method, see auxiliary material for the description of the method) in a relatively short period (1979–2007). Although the basic precipitation processes (e.g., cloud microphysics) are likely to be similar under the two different cases, we cannot rule out the possibility that there are physical processes that could result in different ΔP/ΔT ratios at inter-annual and centennial time scales. For example, ENSO may have a much greater impact on the short-term variations than the long-term trends. However, some analyses of long-term linear trends in the 20th century [*Fujibe et al.*, 2005; *Lau and Wu*, 2007] yield ΔP/ΔT ratios similar to results of *Liu et al.* [2009]. This suggests that at least for the recent (20th century) climate, the ΔP/ΔT ratios from inter-annual variations and long-term linear trends are similar.

[9] Another concern is that the GPCP pentad data contain biases and errors that enhance the ΔP/ΔT ratios. For instance, GPCP data contain a large amount of satellite observations over oceans and parts of land areas, and these satellite observations may contain discontinuities as satellite sensors and orbits have changed over time. For example, the GPCP satellite-based precipitation before 1987 is likely to be less reliable because of the lack of microwave observations, while satellite observations for the last 10 years or so have much improved sampling and thus are more reliable. Other concerns regarding the GPCP data are the coarse resolution (2.5° × 2.5°), 5-day average, and possible long-term drifts in the accuracy of observation instruments.

[10] To alleviate these concerns regarding to the GPCP data and analysis methodology, in the following we compare changes in precipitation intensity derived from the GPCP data with results from reanalyses using operational weather forecast models, namely NCEP/NCAR [*Kalnay et al.*, 1996] and ECMWF ERA-40 [*Uppala et al.*, 2005] reanalysis. The comparison is valuable because the precipitation from the reanalyses is a model-calculated quantity that depends on parameterized moist convection and large-scale precipitation processes in the models used in the reanalysis systems. These parameterizations are similar to those of the coupled climate models analyzed by *Sun et al.* [2007]. However, the atmospheric states (pressure, temperature, humidity, and winds, but not precipitation) were constrained by available observations assimilated in the reanalyses. This is not the case in the coupled climate models. Therefore, the comparison constitutes an independent evaluation of the change in precipitation intensity derived from GPCP. It also provides an estimate of the ΔP/ΔT ratio simulated by model physics similar to that used in the climate models, but under more

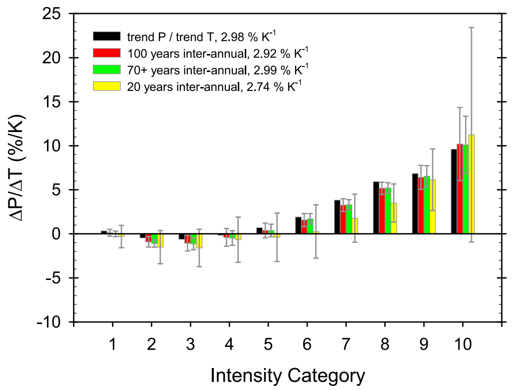

Figure 2. Same as Figure 1 except for three cases calculated by the inter-annual method with different time intervals and a case calculated from 100 year linear trends of P and T from IPCC-AR4 NCAR CCSM3/SRESB1/day_run2 (2000–2099) (90S–90N). $\Delta P/\Delta T$ ratio for the 20-year case (yellow) is from 20 consecutive years in 2000–2099, the 70+ years case (green) from the difference between 2000–2029 and 2070–2099 with year difference greater than 70 years, the 100 year case (red) from the straight forward inter-annual method for the entire 100 years, and the linear trend case is the ratio from the linear trends of P and T between 2000 and 2099 (black). Numbers shown in units of $\% K^{-1}$ are the average increases in precipitation intensity.

realistic environmental conditions. Finally, we analyze the short-term and long-term results of four AR4 climate models to evaluate the difference between short-term variations and long-term trends.

3. Data

[11] To compare with the $\Delta P/\Delta T$ ratios derived from GPCP (60°S–60°N, 1979–2007) by *Liu et al.* [2009], the daily data of NCEP/NCAR (60°S–60°N, on T62 Gaussian grid, 1979–2009 [*Kalnay et al.*, 1996]) and ECMWF ERA-40 (60°S–60°N, on 2.5° × 2.5° grid, 1979–2001 [*Uppala et al.*, 2005]) reanalysis are analyzed using the inter-annual method, which is described in the auxiliary material. The domain 60°S–60°N is chosen because there are many missing data at higher latitudes in the GPCP data. More recent reanalyses, namely CFSR (1979–2009), ERA-Interim (1989–2010), and MERRA (1979–2010) have also been analyzed. Their results are similar to those of NCEP/NCAR and ECMWF ERA-40, but having greater one-standard deviations and hence not shown here.

4. Results and Discussion

[12] Figure 1 depicts the change in the precipitation amount for each precipitation intensity bin for one degree Kelvin increase in near global-mean temperature ($\Delta P/\Delta T$) derived using the inter-annual method from the GPCP pentad data (1979–2007) (yellow bars), and from reanalysis daily precipitation from NCEP/NCAR (1979–2009) (green) and ECMWF ERA-40 (1979–2001) (red). The model-simulated $\Delta P/\Delta T$ values inferred from long-term changes from *Sun et al.* [2007] is shown in brown bars (on the right-hand coordinate, the others on the left-hand coordinate). It can be seen that the shapes of the $\Delta P/\Delta T$ ratio as a function of the precipitation intensity categories are very similar among the four cases, with small changes except the top two or three bins of heavy precipitation. The absolute magnitude of the $\Delta P/\Delta T$ ratio is comparable among the GPCP, NCEP/NCAR, and ERA-40 cases; whereas the $\Delta P/\Delta T$ values from climate models are smaller by about a factor of 10. For the GPCP and reanalysis data, the top 2 bins (i.e., the top 20% heavy precipitation) show large increases of about 20–100% K^{-1}, whereas the lower 6 bins (i.e., the bottom 60% moderate and light precipitation) show either little change or relatively small decreases up to 30% K^{-1}. The overall effect of the changes in individual bins constitutes a shift to higher precipitation intensity, i.e. an increase in the overall precipitation intensity. This overall shift to higher precipitation intensity is best measured by changes of bins 10 and 9 which usually have large values and small 1-standard deviation ranges. Using this measure, it can be seen that the two reanalyses are within 50% of GPCP results, i.e. within the uncertainty of the GPCP data. Therefore one can conclude that the GPCP and the two reanalyses are in good agreement, especially considering that they are from independent data sets. On the other hand, the model results are about a factor of 8 lower than GPCP values, substantially above the uncertainty of the GPCP data.

[13] To ascertain that the large difference between the model-simulated values derived by *Sun et al.* [2007] and the other three cases is not due to different analysis methods, we have downloaded output data from the AR4 NCAR CCSM3 model simulation for the period 2000–2099, and analyzed the data with the inter-annual method for the global domain of 90S–90N. The results are compared with the long-term linear trends induced by increases in greenhouse gases similar to those deduced by *Sun et al.* [2007]. In addition since this model simulation covers long-term climate change from 2000 to 2099, it offers an opportunity to examine the $\Delta P/\Delta T$ ratios over decadal, multi-decadal and centennial time scales for the 21st century. Plotted in Figure 2 are $\Delta P/\Delta T$ ratios for periods of short-term ($\Delta T < 20$ years), the long-term trends between 2000–2029 and 2070–2099 (i.e. $\Delta T > = 70$ years), $\Delta T < 100$ years, and the ratio for the linear trends of P and T between 2000 and 2099. The last $\Delta P/\Delta T$ ratio is similar to the calculation of *Sun et al.* [2007] except they calculated the change in precipitation intensity for each grid first and then made the global averaging. It is clear that within ±1-standard deviation ranges, the four cases agree with one another very well. The agreement shows that the $\Delta P/\Delta T$ ratios calculated by the inter-annual variation method, either in short term (<20 years) or long term (>70 years), are practically identical to the $\Delta P/\Delta T$ ratio calculated from long-term (100 years) linear trends of precipitation and temperature. Furthermore, the average increase in precipitation intensity for all four cases is about 3% K^{-1}, agreeing very well with the value of 2.5% K^{-1} for the CCSM3 (CRES B1 scenario) derived by *Sun et al.* [2007]. This shows beyond any doubt that the large difference between the model-simulated values derived by *Sun et al.* [2007] and the other three cases of Figure 1 is not caused by any difference in the data analysis methods or difference between short-term variations and long-term trends. We have also analyzed daily data from three other AR4 model simulations, namely MPI_ECHAM (2001–2100), GFDL_CCM2.1 (1961 ∼ 2000), and NCAR_CCSM3 (1960 ∼ 1999), the results are similar (not shown).

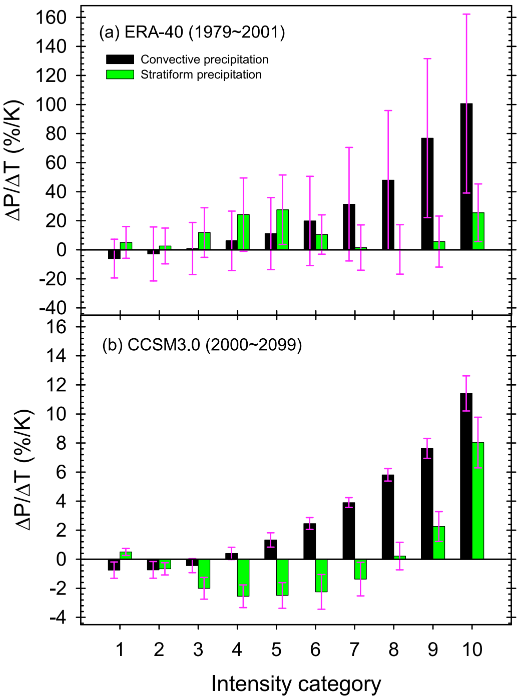

Figure 3. Same as Figure 1 except for convective (dark green) and stratiform (light green) precipitation from (a) ECMWF ERA-40 reanalysis and (b) NCAR AR4 CCSM3.0 model. For ERA-40 the mean annual amounts of convective and stratiform precipitation are 491 mm and 496 mm, respectively. For NCAR AR4 CCSM3.0 the mean annual amounts of convective and stratiform precipitation are 620 mm and 300 mm, respectively.

[14] The use of pentad and daily data produces similar ΔP/ΔT ratios. This is confirmed by similar results found in more recent GPCP data between 1997 and 2007 when daily data are available. These results are also in excellent agreement with the pentad data for the entire period of 1979 to 2007, suggesting improved satellite data since 1987 are consistent with earlier data. In addition, the hourly data from Taiwan show consistent and similar large changes of precipitation intensity when analyzed by hourly, daily, and pentad resolutions [*Liu et al.*, 2009]. There is also other evidence suggesting that large ΔP/ΔT values similar to GPCP of Figure 1 exist over different data records. For example, interannual variations in station data over land from USA during 1951–2000, and southeastern China from 1961–2005 also yield changes consistent to those of GPCP [*Liu et al.*, 2009, supplement]. More importantly, changes in precipitation intensity of the long term rain-gauge data over Japan from 1898–2003 analyzed by *Fujibe et al.* [2005], who also categorized the precipitation intensity into 10 bins, are in excellent agreement with those of GPCP.

[15] Based on the above discussions, we conclude that the ΔP/ΔT ratios as a function of the precipitation intensity categories derived from GPCP by *Liu et al.* [2009] is very likely to be credible, despite of various concerns cited above.

[16] It is interesting that the operational weather models of NCEP and ECMWF used in the reanalysis mode appear to be capable of realistically simulate the change in precipitation intensity with global-mean temperature. In comparison, the climate models are capable of simulating the shape of the change in precipitation intensity, but underestimate the magnitude by about a factor of 10. The fact that both the operational and climate models can correctly simulate the shape of the change in precipitation intensity suggests that the parameterizations for precipitation in the operational and climate models are sound in general. In fact, given the typical spatial resolution of global models of about 1° × 1°, which is too coarse to resolve convective storms, it is surprising that any global model is capable of simulating the magnitude of the change in precipitation intensity with global temperature. In this context, we recognize that the resolution of models of reanalyses is also too coarse to resolve convective storms. However we think that the assimilation of observed moisture and wind fields around convective storms provides a significant advantage for the models used in the reanalysis mode. This can be tested by examining the convective and stratiform precipitation separately as follows.

[17] In Figure 3 changes in convective and stratiform precipitation for the ECMWF ERA-40 reanalysis are compared with those calculated by the model NCAR CCSM3.0. It can be seen that a big difference exists indeed in the changes of convective precipitation between the reanalysis and the model; the former is about ten times of the latter for the two top 20% bins. The ±1-standard deviation ranges for the lower intensity bins of the reanalysis are too large to allow a meaningful comparison. The changes in precipitation intensity for stratiform precipitation predicted by the climate model are also too small but by a smaller margin: a factor of about three smaller than that of the reanalysis for the top 10% heavy precipitation bin. The NCEP/NCAR reanalysis is also examined this way. The results are similar, but the ±1-standard deviations are large and thus not shown.

5. Conclusions

[18] Based on the discussions above, we can make the following conclusions. First, the large increase in global average precipitation intensity increase derived from the GPCP data, with the top 10% heavy precipitation increased by about 108% for each degree Kelvin increase in global mean temperature and the bottom 30%–60% bins decreased by about 20% K^{-1}, is credible. Increases in heavy precipitation can lead to more and worse floods and mudslides, while decreases of light and moderate precipitation can increase the risk of droughts. The 100-year linear trend (1906–2005) of global temperature is 0.74°C ± 0.18°C, and is expected to increase even faster [*Solomon et al.*, 2007]. This implies that the global top 10% heavy precipitation had already increased by about 80% and will continue increase at a faster rate. Meanwhile there are corresponding increases in the risk of droughts. It follows that the increasing occurrence and severity of floods, mudslides, as well as shortage of water resources has been and would increasingly be one of the worst hazards to the global ecosystem as the result of global warming.

[19] Operational models of NCEP and ECMWF used in the reanalysis mode appear to be capable of simulating realistically the change of precipitation intensity with global temperature seen in the GPCP pentad data, apparently because they have the benefit of assimilating the observed moisture and wind fields around convective storms. In comparison, the climate models are capable of simulating the shape of the change in precipitation intensity, but underestimate the

magnitude of the change by about one order of magnitude. The reason of the underestimate is shown to be due to the fact that the typical spatial resolution of climate models is too coarse to resolve convective precipitation.

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