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Temperature dependence of global precipitation extremes

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[1] Data from the Global Precipitation Climatology Project (GPCP) covering the period 1979–2007 are examined for changes of precipitation extremes as a function of global mean temperature by using a new method which focuses on interannual differences rather than time series. We find that the top 10% bin of precipitation intensity increases by about 95% for each degree Kelvin (K) increase in global mean temperature, while 30%–60% bins decrease by about 20% K^{-1}. The global average precipitation intensity increases by about 23% K^{-1}, substantially greater than the increase of about 7% K^{-1} in atmospheric water-holding capacity estimated by the Clausius-Clapeyron equation. The large increase of precipitation intensity is qualitatively consistent with the hypothesis that the precipitation intensity should increase by more than 7% K^{-1} because of the additional latent heat released from the increased moisture. Our results also provide an independent evidence in support for significant increases in the number and/or size of strong global tropical cyclones. However an ensemble of 17 latest generation climate models estimates an increase of only about 2% K^{-1} in precipitation intensity, about one order of magnitude smaller than our value, suggesting that the risk of extreme precipitation events due to global warming is substantially greater than that estimated by the climate models. **Citation:** Liu, S. C., C. Fu, C.-J. Shiu, J.-P. Chen, and F. Wu (2009), Temperature dependence of global precipitation extremes, *Geophys. Res. Lett.*, *36*, L17702, doi:10.1029/2009GL040218.

1. Introduction

[2] Long-term 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 lead to more and worse floods, while persistent chronic decreases of light and moderate precipitation pose a serious threat to the drought problem because light and moderate precipitation are a critical source of water for the replenishment and retention of soil moisture.

[3] Significant increases of the very heavy precipitation and decreases of light and moderate precipitation (10%–60% bins) have been observed over most land areas of the globe in the last few decades [e.g., *Karl and Knight*, 1998; *Manton et al.*, 2001; *Klein Tank and Können*, 2003]. Over the oceans, analyses of satellite data at tropical/low latitudes (30°S–30°N) in 1979–2003 also found similar changes [*Lau and Wu*, 2007]. The widespread increases of heavy precipitation are attributed to global warming [*Trenberth*, 1998; *Allen and Ingram*, 2002; *Trenberth et al.*, 2003]. These authors point out that, according to the Clausius-Clapeyron equation (C-C), tropospheric warming can lead to an increase of about 7% K^{-1} in the atmospheric water-holding capacity. This is supported by available observations of recent decades [*Trenberth et al.*, 2005; *Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. *Trenberth et al.* [2003] hypothesized that the precipitation intensity should increase at about the same rate as atmospheric moisture because precipitation rates from storms were determined by low-level moisture convergence. Furthermore, they argued that the increase in heavy rainfall could even exceed the moisture increase because additional latent heat released from the increased water vapor could invigorate the storms. Invigorated storms would take moisture away, thereby reducing available water vapor for later precipitation. In addition, the extra latent heating would stabilize the atmosphere thereby reducing the precipitation totals on time-scale longer than an event [e.g., *O'Gorman and Schneider*, 2009]. In combination, the above processes could contribute to the increase in the precipitation intensity by increasing heavy precipitation while suppressing light and moderate precipitation. However, the hypothesis was not corroborated by results from an ensemble of 17 latest generation climate models as reported by *Sun et al.* [2007]. They reported that the global mean increase of precipitation intensity was only about 2% K^{-1} for the ensemble average, substantially less than the 7% K^{-1} of C-C. In this work, we test the hypothesis by using a new method to analyze the observed changes of global precipitation intensity recorded in the Global Precipitation Climatology Project (GPCP).

[4] Observed increases in heavy precipitation for different areas are highly variable. This problem of large variability is compounded by the fact that the precipitation intensity is often analyzed in different temporal resolutions, ranging from hourly to daily, sometimes even over 5 days [*Trenberth et al.*, 2003; *Lau and Wu*, 2007]. The precipitation intensity spectrum can be very different when precipitation events, which usually last for several hours in the tropics [*Ricciardulli and Sardeshmuhk*, 2002], are averaged over a day or longer. As a result, published observations of changes in precipitation intensity are difficult to compare quantitatively with model results. An exception is an innovative investigation in which satellite observations of precipitation from the Special Sensor Microwave Imager (SSM/I) over the tropical oceans were compared to model simulations [*Allan and Soden*, 2008]. They found that heavy rain events increased during warm periods of sea surface temperature (SST) and decreased during cold periods, and that the models qualitatively reproduced the observed

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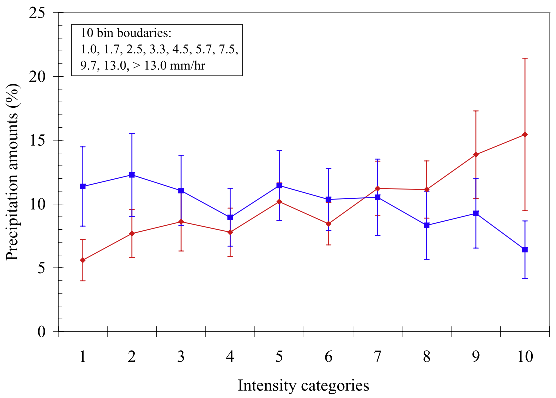

Figure 1. Comparing the average precipitation intensity spectrum of two warmest years (red) to that of two coolest years (blue) observed by 15 stations in Taiwan for the period 1961–2005. Vertical bars denote one standard deviations.

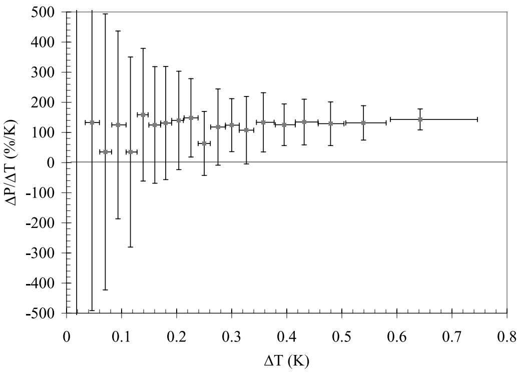

Figure 2. ΔP/ΔT of the top 10% bin of precipitation intensity in Taiwan as a function of ΔT. ΔP is the difference between the top 10% bins of any two years in 1961–2005, and ΔT is the difference in global temperatures of the two years. Each horizontal bar represents the range in ΔT for a group of 40 data points. The vertical bar denotes the one standard deviation for the 40 data points of an individual group.

behavior but weaker in the rate of amplification of extreme rainfall events. In another work, *Lenderink and Meijgaard* [2008] investigated changes of hourly precipitation extremes at a long-term station in the Netherlands. They found that hourly precipitation extremes increased twice as fast with rising temperatures as expected from C-C when daily mean temperatures at the station exceeded 12°C.

2. Methodology

[5] In a recent analysis of the precipitation intensity in southeastern China and Taiwan in 1961–2005, we found significant interannual differences in precipitation extremes with a large increase in the top 10% bin and a large decrease in the bottom 10% bin when low global temperature years (global temperature data are from *Smith and Reynolds* [2005]) are compared to high global temperature years. Figure 1 illustrates the result for Taiwan (from 15 ground stations) by comparing the average precipitation intensity spectrum of two coolest years to that of two warmest years. The 10 bins of precipitation intensity are calculated by dividing the 45 year (1961–2005) average spectrum of precipitation intensity into ten bins with equal amount of precipitation. This sets the ranges of individual bins. These ranges are used to calculate precipitation spectra of individual years. The one standard deviation (1σ) increases slightly when the western Pacific SST instead of global temperature is used, but increases substantially when Taiwan's temperature is used, suggesting that the change in the precipitation intensity is more "connected" to the global temperature than local and regional temperatures. This interesting "connection" is not limited to Taiwan, but rather general (see auxiliary material for details).[1] For this reason, global mean temperature rather than local temperature is used throughout this study. In addition, we notice that the difference in the extreme precipitation (i.e., very heavy or very light bins) tends to be quasi-linearly proportional to the temperature difference (not shown). Taking advantage of this finding, we calculate the difference ΔP between the top 10% precipitation bins of any two years in 1961–2005, then divide ΔP by the global temperature difference ΔT and plot ΔP/ΔT as a function of ΔT (Figure 2). A distinct advantage of this method over the time series method is the reduction of scattering of points and the convergence of the mean value of ΔP/ΔT toward a constant ($\sim$140% K^{-1}) ($\sim$ means approximately) when ΔT increases. In Figure 2, ΔP between any two years in 1961–2005, with a total $45 \times 44/2 = 990$ independent data points in 45 years, are included. The number of points is 22 times the data points (45) if time series are used to derive ΔP/ΔT. The large number of independent points makes it possible to derive a statistically meaningful value for ΔP/ΔT.

[6] In the following, we use this method to study temperature dependence of precipitation extremes by analyzing global data from GPCP which are available in pentad and 2.5° × 2.5° spatial resolution from 1979 to 2007.

3. Results and Discussion

[7] Figure 3 is similar to Figure 2 except for the GPCP data over the period 1979–2007. The 29 year average

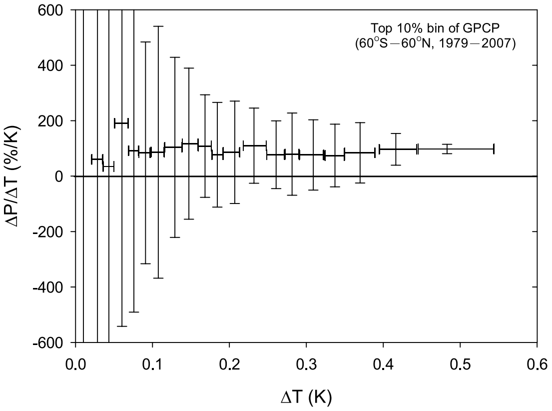

Figure 3. Same as Figure 2 except for the global GPCP data over the period 1979–2007. Each horizontal bar represents the range in ΔT for a group of 20 data points. The vertical bar denotes the two standard deviation for the 20 data points of an individual group.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL040218.

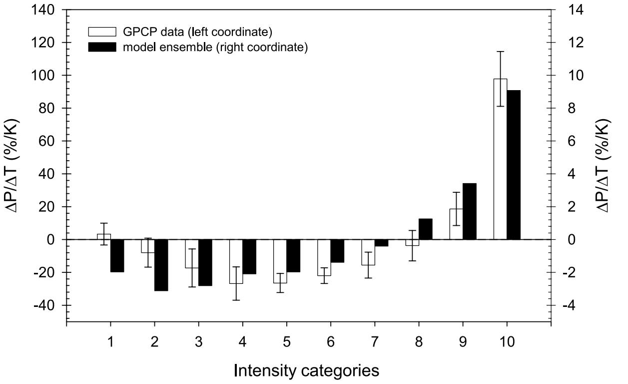

Figure 4. $\Delta P/\Delta T_c$ for all 10 bins of precipitation intensity. Open bars denote values of $\Delta P/\Delta T_c$ derived from the GPCP data over the period 1979–2007. Solid bars are values derived from results from an ensemble of 17 latest generation climate models (B1 scenario, 21st century) as reported by *Sun et al.* [2007]. The vertical line on top of each open bar denotes the 2 standard deviation.

precipitation intensity spectrum at 1 mm/day resolution and the ranges of ten bins for the GPCP data over the period 1979–2007 are shown in Figure S1 of the auxiliary material. A statistically meaningful value for $\Delta P/\Delta T$ (94.2% K^{-1}) can be obtained for the top 10% bin at high values of ΔT as demonstrated by the relatively small value of 2σ of 16.7% K^{-1} near $\Delta T = 0.5$ K. Similar results can be obtained for other bins of precipitation intensity, and they are shown in Figure 4.

[8] It should be noted that percentages of changes are displayed in Figures 1–4. The percentage is calculated from the absolute amount by normalizing to the total precipitation of the corresponding year. Normalization can filter out the fluctuation caused by the interannual variability in the total precipitation and thus tends to give more self-consistent results for the change in precipitation intensity. In the following, normalized results are presented whenever ΔP is expressed in percentage. Nevertheless, we have examined all major results in this work to make sure that the normalization does not significantly bias the results.

[9] The convergence of the mean value of $\Delta P/\Delta T$ toward a constant and its small 2σ value near $\Delta T = 0.5$ K are intriguing and have an important implication. They imply that we can "forecast" changes in precipitation intensity and precipitation extremes with a fair degree of confidence (i.e., small 2σ) given the future global temperature predicted by climate models. They are intriguing because heavy rainfalls are chaotic quantities governed by nonequilibrium atmospheric dynamics and convection, thus are not expected to have such a strong connection to a single variable, namely the global mean temperature.

[10] The strong connection between changes of extreme precipitation and temperature does not necessarily imply any cause-consequence relationship. Any parameter that correlates significantly with the global temperature in the period 1979–2007, even accidentally, can be a potential cause of the changes of precipitation intensity and precipitation extremes. Many parameters may have certain degrees of correlation with the global temperature, including air pollutants such as aerosols which have been proposed to affect precipitation via formation of cloud condensation nuclei [e.g., *Rosenfeld and Lensky*, 1998]. Changes in aerosol could also affect precipitation directly through altering the atmospheric radiation [e.g., *Wild et al.*, 2008]. We defer the discussion of the roles of aerosols to experts in that field.

[11] The mean value of $\Delta P/\Delta T$ for the top 10% bin around $\Delta T = 0.5$ K is 94.2% K^{-1}. This implies a 94.2% increase of the very heavy precipitation for a 1 K increase of global mean temperature, provided the quasi-constant value of $\Delta P/\Delta T$ can be extrapolated to 1 K. Given the tight quasi-constant profile of $\Delta P/\Delta T$ in Figure 3, any deviation from the linear relationship up to $\Delta T = 1$ K is expected to be negligible. Hereon the quasi-constant value of $\Delta P/\Delta T$ will be denoted by $\Delta P/\Delta T_c$. Values of $\Delta P/\Delta T_c$ for individual bins of precipitation intensity are plotted in Figure 4. In addition, values of $\Delta P/\Delta T_c$ for top 5% and top 1% bins are 135(8.6)% K^{-1}, and 198(17)% K^{-1}, respectively (not shown). Values in the parentheses denote 1σ. It can be seen in Figure 4 that the increases of the top 20% bins (i.e., 100% and 90% bins) are at the expense of moderate and light precipitation (30–70% bins). This is also true for non-normalized case.

[12] Changes of individual bins result in a shift of the median precipitation intensity (defined as the upper bound of 50% bin) from 14.3 mm day^{-1} to 18 mm day^{-1}, an increase of $\sim$23% K^{-1}. This is about three times the $\sim$7% K^{-1} increase in water-holding capacity of the atmosphere estimated by C-C. The large increase in precipitation intensity is qualitatively consistent with the hypothesis of *Trenberth et al.* [2003] that the precipitation intensity should increase more than 7% K^{-1}. Surprisingly the ensemble of climate models estimates a mere $\sim$2% K^{-1} increase in average precipitation intensity [*Sun et al.*, 2007], about one order of magnitude smaller than the value $\sim$23% K^{-1} derived from GPCP. To double check this large disagreement, we convert results of the ensemble of climate models to the scale of Figure 4 and plotted them in solid bars. The increase of the top 10% bin calculated by the ensemble of climate models is only $\sim$9% K^{-1}, again about one order of magnitude less than our value. Reductions of light and moderate precipitations also differ by $\sim$10. Interestingly though, the overall shape of the changes of the ensemble of climate models is essentially identical to that of GPCP, suggesting that the process causing the changes are correctly simulated by the models but the strength of the process is severely underestimated. The fact that the results of the ensemble of climate models are in daily resolution instead of pentad makes the differences even greater by about 20% (based on our analysis of daily and pentad data sets of GPCP for the period 1997–2007 when both data sets are available). While there has been some evidence that models underestimate precipitation response [e.g., *Wentz et al.*, 2007], the large differences found here are surprising. They raise a serious concern that the risk of extreme precipitation events due to global warming, including floods as well as droughts, is substantially greater than that estimated by the ensemble of climate models. The societal and ecological impacts of the increased risk would be enormous.

[13] In the auxiliary material, we validate of our analysis method by showing that our results are consistent with a previous analysis of GPCP for linear trends in the precip-

itation intensity in the tropical region (30°S–30°N) over the period 1979–2003 by *Lau and Wu* [2007]. In addition, our results derived from GPCP are cross checked satisfactorily with those from ground stations in Taiwan, Southern China and the US, for which the data are available to us. This check is important because the GPCP data may contain significant inhomogeneity due to substantial changes in the satellite observing system. We also show that our results are in qualitative agreement with those of *Allan and Soden* [2008] and *Lenderink and Meijgaard* [2008]. Finally, in the auxiliary material the latitudinal and seasonal variations of $\Delta P/\Delta T_c$ in the Northern Hemisphere are studied. The value of $\Delta P/\Delta T_c$ of the top 10% bin tends to be greater at low latitudes and in high temperature seasons, consistent with the fact that convective storms are larger and more frequent in regions with high temperature and water vapor.

[14] There has been ~0.74 K global temperature increase in the 100 years between 1906 and 2005 [*IPCC*, 2007]. Based on the value $\Delta P/\Delta T_c = 94.2\%\ K^{-1}$, the world has already been suffering ~70% increase of the top 10% bin precipitation and ~20% decrease of 30%–70% bins precipitation, manifested in increased floods and droughts during that period. More seriously, the increases derived for the top 5% and top 1% bins are ~100% and ~145%, respectively.

[15] In regions covered by tracks of tropical cyclones (TCs), according to our estimate, the top 5%–10% bins of precipitation intensity are very likely to consist of TCs with the top 10%–20% bins of precipitation intensity. The 70%–100% increases in precipitation of the top 5%–10% bins imply that TCs with top 10%–20% bins of precipitation intensity had increased in frequency and/or amount of precipitation by 70%–100% between 1906 and 2005. Assuming that the amount of precipitation of a TC is positively correlated to its size, our findings here provide an independent evidence in support of the increase in the number and/or size of TCs in the categories 4 and 5 reported by *Emanuel* [2005] and *Webster et al.* [2005].

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