TRENDS IN PRECIPITATION INTENSITY IN THE CLIMATE RECORD

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Abstract

Systematic changes (mostly increases) in precipitation intensity (heavy and very heavy daily precipitation events) have occurred during the past 100 years in various regions of the world including the contiguous United States. While the latter constitutes a small fraction of the Earth’s surface, it is important to note that similar changes have taken place in many extratropical regions. There is an ambiguity in impact assessments of heavy precipitation: it can be considered beneficial or harmful. By raising thresholds of definitions and assessing changes in “very heavy” and “extreme” events, an attempt is made to remove this ambiguity. The occurrences of the events studied here are likely to be economically disruptive and potentially life threatening. However, very dense networks are required to reveal changes in the frequency of these events. It is found that both model projections of a greenhouse-enriched atmosphere and the empirical evidence from the period of instrumental observations indicate an increasing probability of heavy precipitation events for many extratropical regions including the United States.
1. INTRODUCTION

In this paper we present an overview of findings related to changes in “very heavy” precipitation, changes that are often disruptive to the environment and the economy (Edwards and Owens 1991; Easterling et al. 2000a,b; Soil and Water Conservation Society 2003; http://earthobservatory.nasa.gov/NaturalHazards/). We do not focus on particular environmental and/or agricultural thresholds to define “heavy precipitation” intensity level (e.g., floods, landslides, and soil erosion), but instead, a uniform definition of the frequency of the event is of primary interest. In general, throughout this paper, we count the upper 0.3% of rainfall events. This equates to a return period of approximately one daily event in 3 to 5 years for annual precipitation and approximately 10 to 20 years for seasonal precipitation, depending on the probability of daily rain events for a given location. Regionally-averaged frequencies of these events and their changes are estimated using long-term data sets.

The structure of this article is as follows. A description of the global network of daily precipitation stations used in the study, and a review of previous work and results related to “heavy” and “very heavy” precipitation over the land, are followed by our most recent results for several countries over the globe, including the contiguous United States that were not previously presented in the peer-reviewed literature. Changes in heavy precipitation from global climate change simulations using three different global climate models are shown in comparison to the observed changes. Finally, we end with a summary of our findings and conclusions.

2. DATA

Sub-daily precipitation time series provide more information about precipitation intensity than daily totals (Trenberth et al. 2003). However, sub-daily data are only readily available in sufficient quantities for the conterminous United States (Frederich et al. 1997; NCDC 1998), and
homogeneity problems remain to be overcome prior to their use (Groisman et al. 1999b). Therefore, in this study we use daily total precipitation data sets compiled at the National Climatic Data Center (Figure 1; NCDC 2002). Precipitation information is available at practically all of these stations. Several regions of the world (most of North America, East Asia, eastern Australia, eastern Brazil, India, South Africa, central Mexico, southern half of the former USSR, and Northern Europe) have a sufficiently dense network making it feasible to study changes in “very heavy” precipitation. There are many more precipitation stations in the world (Groisman and Legates 1995), but their daily data are not presently available. Appendix 1 shows the regional availability of long-term stations used in this study. It can be noted that for most of the contiguous United States there are a sufficient number of century-long daily precipitation time series available. Daily precipitation data for three countries (the former USSR, Canada, and Australia) underwent a special pre-processing to restore instrumental homogeneity of time series affected by changes in observational practices and rain gauges (Groisman and Rankova 2001; Groisman et al. 1999a; Groisman 2002).

3. HISTORY

Changes in heavy and extreme precipitation were first documented by Iwashima and Yamamoto (1993) who used the data from scores of stations in Japan and the United States. A more detailed assessment for heavy precipitation increases over the contiguous United States was published by Karl and Knight (1998). Using the data from ~200 long-term stations, Karl and Knight (1998) showed that the sums of the highest monthly daily precipitation events had increasing linear trends over each large region of the country during the period 1910-1995. Trends were found to be statistically significant at the 0.05 level for four of nine regions and nationwide which experienced a 7% increase. At the same time, Karl and Knight (1998)
demonstrated that the contribution of the upper 10% of precipitation events to annual totals has increased nationwide. Thus, both aspects of changes in precipitation intensity that we are concerned with were indicated. This was done only on a relatively sparse network. When attempts were made to raise the threshold, it immediately became obvious that a denser network was required to identify statistically significant results. Section 4.2 explains theoretical considerations behind this need.

Groisman et al. (1999a) assumed a simple and quite flexible three-parameter model for the distribution of daily precipitation totals. The model was tested and fitted to the data of eight countries (Canada, the United States, Mexico, Norway, Poland, the former USSR, China, and Australia), in order to study the sensitivity of the probability of “heavy” rainfall ($P_{\text{heavy}}$). This was done by varying the model parameters, with comparison to actual variations in probability. They found that a disproportionate change in precipitation intensities occurs whenever mean precipitation changes. This was also shown theoretically by Katz (1999).

These studies and an increasing number of model projections indicating changes in precipitation intensity more likely as global temperature increases (e.g., Meehl et al. 2000; IPCC, 2001; Zwiers and Kharin 1998; Kharin and Zwiers 2000; Allen and Ingram, 2002, Semenov and Bengtsson, 2002) triggered a set of studies to determine changes in the probability of heavy precipitation over the world using all available daily data. Easterling et al. (2000c) summarized these efforts. Some basic tenets emerging from analyses include:

- To obtain statistically significant estimates, the characteristics of heavy precipitation should be areally-averaged over a spatially homogeneous region. Otherwise, noise at the spatial scale of daily weather systems masks changes.
• Whenever there are statistically significant regional changes in the rainy season, relative changes in heavy precipitation are of the same sign and are stronger than those of mean. A search at various sites around the globe using our data holdings and results from others (e.g., Osborn et al 2000; Tarhule and Woo 1998; Suppiah and Hennessy 1998; and Zhai et al. 1999; Groisman et al. 2001) confirmed this item.

• This search also revealed several regions where mean precipitation does not noticeably change in the rainy season but heavy precipitation does change. In such cases, there was always an increase in heavy precipitation. Among these regions are Siberia, South Africa, and northern Japan (Easterling et al. 2000c) and eastern Mediterranean (Alpert et al. 2002).

In the recent Report by the U.S. Soil and Water Conservation Society (2003; Tables 1, 2, and 3) changes in nationwide (contiguous U.S.) annual precipitation with a partition of daily rainfall into “heavy” (above the 95 percentiles and/or above 50.8 mm),”very heavy” (above the 99 and 99.7 percentiles and/or above 101.6 mm), and “extreme” (above the 99.9%-ile) events were assessed. The results showed that as the mean total precipitation over the conterminous U.S. increased, the “heavy” and “very heavy” precipitation increase was significantly greater as was the proportion of the total precipitation attributed to these events increased. Furthermore, a thorough analysis of the nationwide time series indicated that practically the entire nationwide increase in heavy and very heavy precipitation has occurred during the past three decades (Table 3). For the contiguous United States, Groisman et al (2001, 2004) considered different definitions for heavy and very heavy precipitation and their changes during the past century. In their last paper, Groisman et al. (2004) raised the threshold definition of “very heavy” precipitation events. Specifically, the threshold is set to contain the upper 0.3% of precipitation events throughout the contiguous U.S. This means an 80 mm day\(^{-1}\) threshold for daily
precipitation in the major agricultural area of the Midwestern United States and three digit thresholds for southern and southeastern parts of the country (Table 4). When selected from a 12-month period, events above the upper 0.3% threshold have a return period of only once in approximately 3 to 5 years. When selected among a 3-month season of daily events, the return period of “very heavy” precipitation events varies from 10 to 20 years, depending upon the total frequency of days with measurable precipitation in the region. For these defined thresholds, Groisman et al. (2001, 2004) found statistically significant century-long trends in the frequency of “very heavy” precipitation events within three major regions (Figure 2; South, Midwest, and Upper Mississippi) of the Central United States. These regions are particularly important because they cover most of the Mississippi River Basin and most of the wheat and corn belts of the country. Their analysis showed that regionally and seasonally, changes in “very heavy” precipitation vary significantly and the magnitude of the trends is most notable in the eastern two-thirds of the country, and primarily in the warm season when the most intense rainfall events typically occur. We provide some extension of this work in Section 5.7.

4. ANALYSIS METHOD

The regional averaging technique employed throughout this paper is described in Section 4.1. Section 4.2 discusses the representativeness of the area-averaged time series used in this study. In most cases we present the actual time series, which allows the reader to judge the form of systematic trends revealed. We did not focus on the linearity of the changes and used (in addition to the linear trend assessment) a non-parametric test to check for a monotonic change of the time series. In a few cases, when significant non-linearity was detected, we point it out explicitly. Once a statistically significant trend has been discovered, we characterize it by the mean rate of changes. A linear trend estimate is an essential characteristic in this case. We
tested the presence of systematic change in the time series using two standard methods: least squares regression (Draper and Smith, 1966; Polyak 1996) and a non-parametric method based on Spearman rank order correlation (Kendall and Stuart 1967). We used two-tailed tests at the 0.05 or higher significance level. We tested for autocorrelation of the detrended time series of very heavy precipitation, but the residuals of the frequencies of heavy and very heavy precipitation events were never found to be autocorrelated.

### 4.1. Area-averaging routine

Meteorological stations are not uniformly distributed. Stations tend to cluster around major metropolitan areas and are sparse in mountainous terrain. Missing values are present in most of the records. Both factors had to be addressed to properly represent regional averages of the frequency and/or amount of “very heavy” precipitation derived from in situ observations. Area-averaged calculations presented in this paper all use the same method. First, we selected a reference period with the greatest availability of data to estimate the long-term mean values for each element and for each season. For most of the countries/regions, the period selected was 1961-1990 but, for example, in the Nord-Este region of Brazil the reference period used was 1951-1980. This was necessitated by the fact that for a significant number of stations the data ended in 1980. For each station, we determined the empirical distribution function and the set of upper threshold values (90, 95, 99, 99.7 and 99.9 percentiles) for daily precipitation during the reference period. Then, exceedences (or precipitation totals for some analyses) of the threshold values were totaled, and the climatological mean numbers of exceedences (totals above the given thresholds) during the reference period were calculated. For each region, season, year, and precipitation intensity threshold, we calculated the anomalies from the long-term mean number of exceedences (or precipitation totals above the thresholds) at each station and then
arithmetically averaged these anomalies within 1ºx1º grid cells. Then these anomalies were regionally averaged with the weights proportional to their area. Data from the large regions use the regional area weights to form the national average when those analyses are presented. The long-term mean values (normals) were area-averaged in a similar fashion and added at the final stage to the area-averaged anomalies. This approach emphasizes underrepresented parts of the region/country. It also allows the preservation of the regional time series unaffected by the changing availability of data with time.

In some situations, time series of exceedences of very high climatological thresholds can show inhomogeneities between the reference period used to define the threshold and the other periods, due to biases in estimates of the threshold in the changing climate conditions (Zhang et al. 2004, in preparation). Special experiments with varying reference periods were conducted to assure that the conclusions presented in this paper are not affected by this problem.

4.2 Representativeness of regional estimates of very heavy precipitation frequency

a. Theoretical framework

Each estimate of the area-averaged anomaly of a variable, X, is based on a set of point (or grid cell) measurements of these anomalies, x_i, (i=1,2, ..N) within the region with area S. The estimate should be a representative for the regional quantity. Formally, this means that a linear combination of our point measurements, X' = Σ w_i x_i, should be as close to variable X as possible (w_i are the weights of averaging in approximation of X by X'). The mean square error, E^2, of the linear estimate of the area-averaged anomaly X over the region S using data (x_i) from N locations (or grid cells) is given by Kagan (1997) as

\[ E^2 = \sigma_s^2 - 2 \Sigma w_i \Omega_i + \Sigma \Sigma w_i w_j R_{ij} + \Sigma w_i^2 \delta_i^2, \]

where \( \sigma_s \) is the standard deviation of the area-averaged anomaly, \( \Omega_i \) is the variance of the point measurement, \( R_{ij} \) is the covariance between point measurements i and j, and \( \delta_i^2 \) is the variance of the point measurement i.

The use of anomalies guards against station dropouts and faulty trends.
where $\sigma_s^2$ is the variance of the variable $X$ *averaged* over the region $S$, $\Omega_i$ is the covariance of $x_i$ and $X$, $R_{ij}$ is the covariance between $x_i$ and $x_j$, and $\delta_i^2$ is the variance of the error of measurement at location $i$. If the statistical structure of the $x$-field is known, the error $E^2$ can be estimated for each set of sites (grid cells) inside the region with any selection of $w_i$. Our selection of weights $w_i$ is described in 4.1. The spatial correlation function of the frequency of “very heavy” precipitation has never been estimated previously, although it is likely that the radius of correlation of these quantities is quite small. We calculated the spatial correlation function of the seasonal and annual frequencies of very heavy precipitation (our $x$-fields) and approximated it in the form

$$r(\rho) = C_0 \exp(-\rho/\rho_0),$$

where $\rho$ is the distance, $\rho_0$ is the radius of correlation, and $C_0$ is a constant below 1. In our estimates for the contiguous United States, Australia, Brazil, South Africa, and Mexico, $C_0$ varies between 0.55 and 1.0. The term $(1-C_0)$ is an estimate of the portion of the variance of the $x$-field that is not spatially correlated. As a result, $C_0$ characterizes both microclimatic variability and errors in $x$-measurements (i.e., $\delta^2$).

The relative root-mean-square error, $Z$, of the mean anomaly of the $x$-field over the region $S$ that is approximated by $x_i$ at $N$ points (grid cells) *evenly* distributed over the region $S$ (here we use the area name, $S$) can be described by

$$Z_S = C_v \left\{ \frac{(1-C_0)/C_0 + 0.23(S/N)^{1/2} \rho_0^{-1}}{N} \right\}^{1/2},$$

where the spatial correlation function is approximated by Eq. 2, and $C_v$ is the coefficient of variation of the $x$-field (Kagan 1997). If the points/cells are not evenly distributed over the
region, $Z$ is increased by a factor influenced by the area-averaging routine, the parameters of spatial correlation function, and the measure of unevenness of the points distribution.

Following the area-averaging procedure described in 4.1, we first estimated the representativeness of grid cell area-averaging. This step provided us estimates of the accuracy of $1^\circ \times 1^\circ$ grid cell values of the averaged frequency of “heavy” and “very heavy” events. These accuracy estimates were then used for evaluation of the regional $Z_S$-values.

b. Results

The application of Eq. 3 shows that for a “typical” $1^\circ \times 1^\circ$ grid cell on fairy level terrain\(^2\) (with a $\rho_0$ of $\sim 30$ km and $C_v$ of $\sim 0.3$ for the annual frequency of “very heavy” precipitation events), we can achieve approximately 10%, 15%, and 25% accuracy of area-averaging with 3, 2, and 1 stations respectively. Similar assessment in mountainous $1^\circ \times 1^\circ$ grid cells\(^3\) (with a $\rho_0$ of $\sim 10$ km and $C_v$ of $\sim 0.4$) gives estimates of $Z$ in the range of 25%, 35%, and 60%, respectively.

Table A1 provides estimates of $\rho_0$ and $C_0$ for the frequency of “heavy” (H) and “very heavy” (VH) seasonal and annual precipitation (above the upper 10\(^{th}\) and 0.3\(^{th}\) percentiles respectively) for several regions of the conterminous United States and two regions of the European part of the former USSR. In the latter, thunderstorm activity associated with very heavy precipitation is less spatially expansive compared to the former (i.e., it rarely manifests itself as a multi-cell event) and we rarely have more than 1 station per a grid cell. Consequently, here, we obtained estimates of $C_0$ below 0.5 for approximations of the spatial correlation function of the frequency of VH annual precipitation events between $1^\circ \times 1^\circ$ grid cells. Large values of seasonal and annual radius of correlation for frequency of “heavy” precipitation events

\(^2\) e.g., the Midwestern United States, European Russia, or Australia.

\(^3\) e.g., the western United States, Caucasus, or Mexico with large micrometeorological variability.
of several hundred kilometers (up to 600 km in the Northwestern United States in winter) assure the representativeness of area-averaged values of this quantity based on a point/gridcell network similar to that for mean seasonal/annual precipitation based on this network (cf., Czelnai et al. 1963; Huff and Changnon, 1965; Kagan 1997). For VH events, further analysis was required.

In a region larger than a grid cell (e.g., the Midwestern United States, which encompasses 82 1° x 1° grid cells, with nearly complete grid cell data coverage during the entire 20th century Figure A2), we obtained Z less than 2% throughout the 20th century for the area-averaged annual VH frequency. In this region, Z-values remain less than 3% even in the last decade of the 19th century. The opposite situation (among the regions considered in this paper) is evident in northwestern Russia between 60°N and the Arctic circle. This region, with area ~10^6 km^2, does not have a complete (or nearly complete) 1° x 1° grid cell coverage to start with (Figure A3). Fifteen 1° x 1° grid cells with data (usually a single station within a cell and the cells unevenly distributed over the region) result in a value of Z close to 15%. The term \( C_v[(1-C_0)C_0^{-1}N^{-1} + \ldots]^{1/2} \) is a major component in Eq. 3 for this region and it decreases slowly with increasing N. The above illustrates that the number of 1° x 1° grid cells with valid station data is an important component in the accuracy of area-averaging. Therefore, this quantity was used throughout the study to control the level of representativeness of our results for each region discussed below.

5. ANALYSES FOR SEVERAL REGIONS IN THE WORLD

5.1. European part of the former USSR

For this region, more than 700 long-term stations during the period 1936-1997 are available for analyses of “heavy” and “very heavy” precipitation (Bulygina et al. 2000). The numbers of stations for the two regions under consideration shown in Figure 3 are 70 and 633. In general, maximum precipitation in this area occurs during the warm season, with very heavy rainfall
coming almost entirely from convective clouds (Sun et al. 2001). Note that more than 90% of the daily precipitation events are less than 10 mm day\(^{-1}\). Table 5 and Figure 3 summarize the results of trend analyses for these two regions. Both show a profound increase of 10% to 15% in annual precipitation in the region for the study period though the century-long increase is smaller (e.g., Groisman 1991; Groisman and Rankova 2001). During the same period, the rate of increase in heavy precipitation, in very heavy precipitation, and in extreme rainfall was higher than for mean annual precipitation. The linear trend of the time series of heavy precipitation was statistically significant at the 0.01 level in both regions. In the southern region, trends in very heavy (upper 1% of rain events) and even in extreme precipitation are also statistically significant at the 0.05 level or above. The trends of very heavy precipitation in the north are not statistically significant, probably because of the relative paucity of stations in that area (Figures 1 and A3). The network here is adequate for capturing total precipitation and the upper 10% and 5% of precipitation events. However, when totaling the precipitation of rare very heavy rain events (that occur once per year or even less frequently), one needs a denser network to suppress the very high weather variability associated with these events. \(Z\)-estimates based on Eq. 3 show that the random errors of the area-averaged frequency of very heavy and extreme precipitation, \(Z\), are approximately four times higher than in the southwestern part of the former USSR.

5.2. Northern Europe

Fennoscandia is very well covered by precipitation stations (Groisman and Legates 1995) but only a fraction of the daily data for this network is available publicly (Klein Tank et al. 2002), or for special research projects such as Arctic Climate Impact Assessment (ACIA 2004; Groisman et al. 2003). In the framework of ACIA, a study of contemporary climatic changes in high latitudes during the past 50 years has been conducted (Groisman et al. 2003). To define “heavy”
precipitation events in high latitudes, a special effort was made to separate and further consider only “discernible” precipitation events, which we have defined as those above 0.5 mm. The reason for this is that the median of daily precipitation events over most regions in high latitudes is close to or even less that 0.5 mm. This coupled with the frequently changing precision of measurements can interfere with our analyses, e.g., in Canada and Norway (Groisman et al. 1999a; Groisman 2002). There were previous reports describing the total precipitation increase in Northern Europe (Groisman 1991; Hanssen-Bauer et al. 1997; Heino et al. 1999; Førland and Hanssen-Bauer, 2000; IPCC 2001) however they all reported a smaller relative change compared to that revealed in Figure 4 for the changes in “very heavy” precipitation frequency both in summer (a season with the most intense precipitation) and throughout the year.

**5.3. Pacific coast of Northwestern North America**

This is the only large high latitude region with both large annual precipitation totals and a sufficiently dense precipitation network available for our analyses. Figure 5 shows the time series of the frequency of heavy and very heavy precipitation in southern Alaska (south of 62°N) and British Columbia, Canada (south of 55°N). In both regions, precipitation increased during the period of record, but the double digit increase in the frequency of heavy and very heavy precipitation is especially noteworthy (Table 6). Given the high thresholds for these events, these changes reflect an increasing societal and/or environmental threat in both areas.

**5.4. Southeastern and southwestern Australia**

Southeastern Australia is densely populated and thus is well covered by a long-term precipitation network (Lavery et al. 1997, Figure A4). The southwestern tip of the continent has good station coverage since the mid of the 1910s. Precipitation occurs in southeastern Australia year round without particular peaks in the seasonal cycle while a winter (JJA) maximum is
observed in the southwest. The regionally-averaged thresholds for annual very heavy precipitation (upper 0.3% of daily events) are 82 and 53 mm respectively. Figure 6 shows time series of both annual precipitation and the frequency of days with very heavy precipitation for these two regions. Precipitation totals increased by 16%/100 yrs in the southeast and decreased by the same amount in the southwest during the period with sufficient data (1907-1998 and 1913-1998 respectively). The 52%/100 yrs increase in frequency of very heavy precipitation in the southeast is statistically significant at the 0.05 level, while the 43%/100 yrs decrease in the southwest is statistically significant only at the 0.1 level.

5.5. South Africa

We focused on the eastern part of the country, which is more humid and is mostly farm land. This area is thoroughly covered by a dense, long-term precipitation network (Figure A5). The regionally-averaged thresholds for “very heavy” precipitation (upper 0.3% of daily events for annual and summer (DJF) precipitation are 85 mm (return period 5 years) and 90 mm (return period 10 years) respectively. Figure 7 shows time series of both annual precipitation and frequency of very heavy precipitation for this region. While annual and summer precipitation totals did not change during the period with sufficient data (1906-1997), there is an increase in the annual frequency of very heavy precipitation that is statistically significant at the 0.05 level. These results broadly correspond to those by Fauchereau et al (2003). In addition, we noted a significant increase in very heavy precipitation during the last three decades (a feature that was also evident for the contiguous United States, cf., Groisman et al. 2004; Section 5.7).

5.6. Eastern Brazil and Uruguay

A sufficiently dense network for the past 70 years is available for the Eastern Half of Brazil and Uruguay (Figures 1 and A6). This became possible after the National Meteorological Service, in
cooperation with a private company Agência Nacional de Energia Elétrica (ANEEL) made their national precipitation data publicly available at the World Wide Web. An explosion of research was a result of this action (Liebmann et al. 1998, 1999, 2001; Liebmann and Marengo, 2001; Marengo et al. 2001; Carvalho et al. 2002).

Figure 8 shows time series of both annual precipitation and the frequency of very heavy precipitation for three regions of Eastern Brazil and Uruguay. For these three regions, the regionally-averaged thresholds for annual upper 0.3% of daily rainfall events are 100, 95, and 120 mm, respectively and have return periods of 3 to 4 years. Very high precipitation variability in a relatively dry climate of Nord-Este is modulated by El-Niño – La-Niña events (Ropelewski and Halpert 1996). In Nord-Este, we found a statistically significant increase in the annual frequency of heavy precipitation events, but all of the increase occurred during the first half of the 20th century. In the subtropical part of Brazil there was a systematic increase of very heavy precipitation since the 1940s. In the northern subtropical region, where an extremely dense network of Sao Paulo state was used in our analysis (cf., Liebmann et al. 2001), we obtained an increase of 58%/100 yrs, or by 34% for the period of record statistically significant at the 0.01 significance level.

5.7. Central United States

In three large neighboring regions in the central United States (shaded in Figure 2), statistically significant increasing trends in very heavy precipitation were documented for the period 1908-2002 (Groisman et al. 2004). Data availability restricted Groisman et al. (2004) in the nationwide analyses of the very heavy precipitation prior to the 1908 starting year. This, however, is mostly due to a data deficiency in the western part of the country (Figure A2). Here, we extend our analyses of “very heavy” precipitation back to 1893 (Figure 9). In 1893, the
analysis covers only 84 1°x1° grid cells compared with more than 330 during the second half of the 20th century. This deficiency adds some noise to the regionally averaged time series. Over the study period (1893-2002) the frequency of very heavy precipitation has increased by 20% (statistically significant at the 0.01 level). All of the increase has occurred during the last third of the century (Figure 9). The longer the time series are, the better is our understanding of the variability of heavy and very heavy precipitation in the 20th century. But, it is probably a paradox that so much effort was made to collect, quality control, pre-process, and analyze the data for the full 110 years only to reveal that during the first 80 years no systematic changes occurred in very heavy precipitation frequency (Table 3, Figure 9). However, this emphasized that the change over the last 30 years is unusual and is (at least for the contiguous U.S., South Africa, and Central Mexico cf. Figure 7, Fauchereau et al 2003, and the next section) a relatively new phenomenon.

5.8. Central Mexico

Central Mexico is reasonably well covered with precipitation data for the past 60 years (Figures 10 and A7). The North American monsoon is the major cause of summer rainfall away from the coastal areas in the central part of the country. Figure 10 shows that during the past 30 years a substantial precipitation decrease has occurred over the Central Plateau of Mexico. The frequency of heavy precipitation events (those above the 25 – 35 mm thresholds in this region) generally followed the tendency of the mean totals (although these changes were statistically insignificant). However, the frequency of very heavy precipitation (above the upper 1 and 0.3 percent of the rain events or above 55 mm and 75 mm respectively) increased during the same 30-year-long period. The frequency of very heavy rain events (above the upper 0.3 percent) have increased substantially (by 110% per 30 yrs). Thus, while in the early 1970s the average
return period of such events was approximately 12 years, in the early 2000s it is estimated to be around 5 years.

5.9. Summary of observed trends in heavy and very heavy precipitation

Figure 11 is a substantial update of the map from Easterling et al (2000c) where signs (+ and -) show the regions with changes in heavy precipitation found in our studies and in the studies of others that follow the pattern outlined above: changes in mean precipitation are less or insignificant while changes in heavy/very heavy precipitation are statistically significant. The shaded regions in this figure are those for which we have obtained the results ourselves, although others have studied some of these regions as well and reached similar conclusions, e.g., Stone et al. (2000) for Canada, Iwashima and Yamamoto (1993) for Japan, Roy and Balling (2004) for India, Osborn et al. (2000) for the United Kingdom, Tarhule and Woo (1998) for Nigeria, Zhai et al. (1999) for China, Kunkel et al. (1999) and Kunkel (2003) for the United States\textsuperscript{4}, Alpert et al. (2002) for Eastern Mediterranean, and Haylock and Nicholls (2000) for Australia.

6. MODEL PROJECTIONS

What are the causes of all the observed trends in precipitation intensity? Unfortunately, observed data and/or their analysis alone cannot provide answers to this question. These questions are better addressed by physical models of the Global Climate System. Most Global Climate Models project an increase in precipitation intensity with global warming (Schaer et al. 1996; Jones et al. 1997; Hennessy et al. 1997; Mason and Joubert 1997; Zwiers and Kharin 1998; Meehl et al. 2000; Kharin and Zwiers 2000, IPCC 2001; Wilby and Wigley 2002; Allen and

\textsuperscript{4} More recent work by Kunkel et al. (2003) found similar increases for the United States during the 20\textsuperscript{th} century, but also found evidence that there was a period of increased heavy rainfall events during the 1890s over the western part of the country.
Ingram 2002; Hegerl et al. 2003, 2004). There are physical explanations for the reason that changes in heavy precipitation should be more pronounced than changes in precipitation totals in ongoing climatic change (Trenberth 1999; Groisman et al. 1999a; Bengtson 2001; Allen and Ingram 2002; Trenberth et al. 2003). Recently, Karl and Trenberth (2003) showed that even without change in total precipitation, there was an increase in intensity of daily precipitation when comparing warmer with cooler climates.

Climate models simulate a global-scale increase in mean precipitation due to greenhouse warming (IPCC 2001). Changes in global mean annual precipitation from an ensemble of coupled model simulations driven by both natural (changes in volcanism and solar forcing) and anthropogenic forcing closely follow the observed trajectory (Allen and Ingram, 2002). However, this similarity is caused only by the effect of volcanic eruptions on global precipitation and the anthropogenic signal cannot presently be detected (Lambert et al., 2004). Furthermore, the spatial pattern of annual precipitation change is very model dependent (IPCC 2001; Hegerl et al. 2004). This means that climate change patterns between different models are poorly correlated at the time of the CO₂ doubling, which will make the detection of such changes in observations difficult. However, simulated changes in heavy and very heavy precipitation tend to become more positive and stronger, reaching a change of over 20% for very heavy precipitation at the time of CO₂ doubling (Allen and Ingram 2002; Semenov and Bengtsson 2002). The spatial pattern of changes in heavy precipitation shows more regions of increase than the pattern of annual precipitation changes, and hence more similarity between models (Figures 12 through 14). This finding of a more consistent pattern of increase in heavy precipitation in climate model simulations is supported by a comparison of two GCM projections of the warming effects on precipitation associated with the doubling of CO₂ in the atmosphere. We follow
Hegerl et al. (2003, 2004) who assessed projected changes at the time of CO₂ doubling but highlight here results for Northern America. The pattern of the difference for annual precipitation and two characteristics of extreme precipitation were analyzed between the “average climate” at the time 2040-2060 in the 2xCO₂ simulation and conditions at the end of the 20th century. This was done for a 3-member ensemble simulation for each of the two models:

- The Canadian Climate Centre model CGCM1, which is the first version of the coupled climate model from the Canadian Centre for Climate Modelling and Analysis (CCCma; Flato et al. 2000; Boer et al., 2000a,b). The atmospheric component of this model has a resolution of 3.75° latitude by 3.75° longitude.

- The third cycle of the Hadley Centre climate model (Gordon et al. 2000; Pope et al. 2000; Johns et al. 2002, see also Stott et al. 2002). This model has the same longitudinal resolution and a higher latitudinal resolution of 2.5°.

While the change in atmospheric composition is implemented differently in both models, it is expected that by the middle of the 21st century, differences between both ensembles are largely due to differences in the model response.

Figure 12 compares the change in annual total precipitation and in the number of exceedences of the 99.7th percentile in two climate models. The comparison reveals how inconsistent the pattern of total precipitation changes is compared to that of the change in the frequency of the wettest days of the year. Both models show a pronounced pattern of changes of opposite signs with a global mean increase of between 1 and 2 percent (Figure 12; Hegerl et al. 2004) but these patterns correlate poorly between the models. When the change in the upper 0.3 percent of precipitation events is studied, both models show an increase in precipitation extremes over most regions of the globe, although regional details still differ (Figure 12). Figure 13 shows
the "consensus" climate change pattern for the annual mean precipitation over North America. The pattern is based on the average of both model's simulations. Values are plotted only where the changes in both models are consistent (i.e., the changes in the ensemble simulations with both models at a gridbox are not significantly different at the 90% level based on a Mann Whitney rank test). This represents a pattern of precipitation change that is robust between both models. The difference is striking in this “consensus” intercomparison. Over most of the continent the change, often even the sign of change in total precipitation is different between both models (Figure 13). In a different way, the “consensus” change in precipitation on the wettest day per year and, to a lesser extent, in the wettest 5 consecutive days per year precipitation increases everywhere over North America (Figure 14). This increased similarity in the patterns of change should lead to more robust signal in heavy compared to annual mean precipitation. A simple detection analysis using model data only suggests that changes in extreme rainfall may therefore be more robustly detectable than changes in annual total rainfall (Hegerl et al., 2004): By the time of CO₂ doubling, annual total rainfall changes simulated in one model could not be reliably detected using “fingerprints” of climate change based on the other model, while changes in heavy rainfall could be confidently detected by that time between the model simulations. If this finding based on two models can be generalized, it suggests that observed changes of very heavy precipitation are easier to detect and attribute to global warming than changes in the mean annual or seasonal precipitation.

The results based on GCMs are more credible when simulated variability and trends roughly correspond to those observed during the past century. Unfortunately the direct intercomparison of transient climate change in heavy precipitation as reproduced by the GCM and the observed change is not a frequent exercise and is hampered by differences in the scale represented by
model data (smooth gridboxes) and observed station indices. One of such examples is presented and discussed below.

In their assessment of rainfall intensity changes in the transient greenhouse gas simulation using a coupled atmosphere-ocean global circulation model (ECHAM4/OPYC3 for 1900-2099), Semenov and Bengtsson (2002; their Figure 4) looked at results of the simulated changes of the contribution of the upper 10% quantile of daily precipitation to the annual total precipitation over the contiguous United States for the 20th century. These were compared with the empirical results of Karl and Knight (1998). A close resemblance of positive trends, mean values, and the amplitude of the interdecadal variability suggests that the observed changes are in part related to an increase in greenhouse gases. The only other region of the United States that was assessed by Semenov and Bengtsson (2002) was the northeastern quarter of the country, which roughly corresponds to the Northeast and Midwest regions of the study conducted by Groisman et al. (2004).

Figures 15 and 16 show the changes in the number of days with heavy precipitation and “wet” days in the eastern United States from model results (Semenov and Bengtsson 2002) and observations (Groisman et al. 2004). Comparing observations in this region with changes in the number of days with heavy precipitation from this model, we did not expect that year-to-year variations in the GCM simulation and observations would coincide. Moreover, the model grid cells generate precipitation twice as frequently as observed in point observations. However, this comparison reveals a similar increase of approximately 10% over the 20th century in both time series. This model projects a substantial increase (up to 40% to the end of the 21st century) of days with “heavy” precipitation. In spite of the above mentioned similarities, these are obviously two very different estimates of climate change over the northeastern United States. For example,
a century long change during the 20th century was generated in the first 70 years in the model simulation, while the opposite is true in observations. This points to the need for ensemble assessments of future climate projections (Kattsov and Walsh 2000; Kharin and Zwiers 2002).

It is clear that if mean precipitation does not change appreciably compared with the highest part of the precipitation distribution, then the frequency of precipitation events will be affected. Indeed, in several regions of the world this appears to be the case. For instance, in South Africa, Siberia, Eastern Mediterranean, Central Mexico, and northern Japan, an increase only in heavy precipitation is observed while total precipitation and/or the frequency of days with an appreciable amount of precipitation (wet days) are not changing and/or are decreasing (Figures 7 and 10; Sun and Groisman 2000; Easterling et al. 2000c; Alpert et al. 2002). The first indication that this feature might also be present in the contiguous United States is shown in Figure 16 for the northeastern part of the country. Observations show that the annual number of wet days has increased during the past 100 years, but during the last 30 years (exactly at the time when most of increase in very heavy precipitation started) a decrease in the number of wet days was observed. This figure is presented to compare the observations with the variations of the regional number of wet days reproduced by the ECHAM4/OPYC3. We see a similarity of tendencies and a very strong decrease in the wet-day frequency projected for the 21st century by the model. However, once again the reliability of the model simulation is somewhat hampered by an exaggerated number of days with model-generated precipitation (on average annually, 240 of “modeled” days are “wet”, which is much higher than observed).

7. DISCUSSION AND CONCLUSIONS.

A physical explanation for an increase in heavy precipitation with global warming is provided by Trenberth et al. (2003). An expanded body of evidence for the 20th century presented in this
paper appears to support this concept for “very heavy” precipitation as well. Global warming, which has been especially pronounced during the recent decades in extratropical land areas and in minimum temperatures (Karl et al. 1991; IPCC 2001), is related to a reduction in spring snow cover extent (Brown 2000, Groisman et al. 1994, 2001), and thus to an earlier onset of spring- and summer-like weather conditions (Easterling 2002). Warming also relates to a higher water vapor content in the atmosphere (Douville et al. 2002; Trenberth et al. 2003), which has been documented in many regions of the world (Sun et al. 2000; Ross and Elliott 2001). This in turn results in an increase in the frequency of *Cumulonimbus* clouds (documented for the former USSR and the contiguous United States by Sun et al. 2001), which is related to the general increase in thunderstorm activity (documented for most of the contiguous United States by Changnon 2001). This development can explain an observed widespread increase in very heavy precipitation in the extratropics. Furthermore, in humid regions an increase in summer minimum temperatures is related to an increase in the probability of severe convective weather (Dessens 1995) and is likely related to changes in the frequency of heavy and very heavy rain events. It is difficult to directly relate estimates of changes in very heavy precipitation with flooding (e.g., Groisman et al. 2001; Kunkel 2003). However, great floods have been found to be increasing in the 20th century (Milly et al. 2002).

We are confident in our finding that precipitation intensity has increased during the period of instrumental observations over most of the contiguous United States. Clearly, more work is needed, but the evidence is growing that the observed historical trends of increasing very heavy precipitation are linked to global warming; the global surface air temperature was the highest in the millennium during the past decade and there is a consensus that it will increase further. Simulated changes in intense precipitation and precipitation extremes are generally greater than
in mean precipitation and are consistent among the models studied here. It is likely that changes in heavy precipitation will probably be more easily detected than changes in annual mean precipitation in the future climatic changes.

In summary, those are the major findings of this study:

- Reliable assertions of very heavy and extreme precipitation changes are possible only for regions with dense networks;
- In the mid-latitudes, there is a widespread increase in the frequency of very heavy precipitation during the past 50 -- 100 years;
- By raising the thresholds for the definition of very heavy precipitation and providing empirical evidence of changes in the frequency of these events, we can better provide a basis for impact assessments of the consequences of these changes, including landslides, floods, and soil erosion; and
- Both model projections of a greenhouse-enriched atmosphere and the empirical evidence from the period of instrumental observations indicate an increasing probability of heavy precipitation events for many extratropical regions including the United States.

Acknowledgements: NASA Grant GWEC-0000-0052 and the NOAA Climate and Global Change Program (Climate Change and Detection Element) provided support for this study. GCH was supported by NSF grant ATM-0002206 and ATM-0296007, and by NOAA grant NA16GP2683 DRE and TRK were partially supported by the Office of Biological and Environmental Research, U.S. Department of Energy.
Appendix 1. Availability of long-term stations.

Figure A1 shows the availability of long-term stations in Northern America used in this study. It can be noted that for most of the contiguous United States there are a sufficient number of century-long daily precipitation time series available. The following set of similar figures (A2 through A7) provide counts of stations with precipitation data within each $1^\circ \times 1^\circ$ grid cell for periods with relatively stable networks for regions used in this study. A station was considered present during the listed period when it had at least 50% of daily precipitation data within it. The figures also depict the regions used for area-averaging for the contiguous United States, former USSR, Australia, South Africa Brazil, and Mexico. Area-averaging can be counterproductive and even misleading when changes of opposite signs have occurred within the region. Therefore, we first selected regions that can be considered as relatively climatologically homogeneous according to independent criteria and then applied the area-averaging routine. To preserve the comparability of results, the regional partition for the conterminous United States remains the same as used in Karl and Knight (1998) and Groisman et al. (2001, 2004). When no published climate regions could be found for a country (e.g., South Africa, Brazil, and Mexico), we created them using a combination of climate classifications from Trewartha (http://fp.arizona.edu/khirschboeck/climate/Trew.map.large.htm), plots of seasonal precipitation averages, and considerations of terrain, vegetation, latitude, and data availability.
REFERENCES:


Liebmann, B., G.N. Kiladis, J.A. Marengo, T. Ambrizzi, and J.D. Glick, 1999: Submonthly Convective Variability over South America and the South Atlantic Convergence Zone. *J. Climate*, **12**, 1877-1891.


FIGURE CAPTIONS

Figure 1. Map of stations with daily precipitation available at the U.S. National Climatic Data Center (as of July 15, 2003). A subset of ~32,000 is available through Global Daily Climatology Network, GDCN, Version 1.0 (NCDC 2002; red dots).

Figure 2. Regions of the contiguous United States (dark-shaded) where statistically significant annual increases in very heavy precipitation for the 1908-2002 period were reported by Groisman et al. (2004).

Figure 3. Annual, heavy, and very heavy precipitation totals over the western half of the former USSR (regions of area-averaging are shown in the maps above the plots). The number of 1° x 1° grid cells with valid station data are shown by dotted red lines.

Figure 4. (a) Data availability at the 88 stations over Scandinavia generalized within the 1° x 1° grid cells and (b) annual totals and frequency of very heavy annual and summer precipitation events during the 1951-2002 period. All linear trends are statistically significant at the 0.01 level or above. All increases have occurred in the past 25 years. The average regional upper 0.3% thresholds are 50 and 45 mm for summer and year respectively.

Figure 5. Heavy and very heavy annual precipitation along the northwestern coast of North America. The number of 1°x1° grid cells with valid station data are shown by red lines.

Figure 6. Annual precipitation and frequency of very heavy precipitation over southeastern and southwestern Australia (regions of area-averaging are shown in the map). The linear trend estimates are statistically significant at the 0.05 level (red) and 0.10 (blue) levels respectively.

Figure 7. Annual and summer (DJF) rainfall and frequency of very heavy rains over the Eastern half of South Africa (region of area-averaging is shown in the map). The linear trend estimate
for an increase in the annual frequency of very heavy precipitation (44%/100 yrs) is statistically significant at the 0.05 level.

Figure 8. Annual rainfall and frequency of very heavy rains over three regions in Brazil, Uruguay and adjacent Argentinean and Paraguay areas (regions are dark-colored in the map). Linear trend estimates for increases in the annual frequency of “very heavy” precipitation in Nord-Este (1911-2001) and Northern Subtropics (1941-2001). Trends are statistically significant at the 0.05 level or higher.

Figure 9. Very heavy precipitation over regions of the Central United States shown in Figure 2. All trends indicated in the graph (even for the last three decades) are statistically significant at the 0.05 level or higher.

Figure 10. Mexico, Central Plateau (region is shown in the map). Summer precipitation and number of days with heavy ((above 90th and 95th percentile) and very heavy (above 99th and 99.7th percentile) precipitation. Since 1970, more than twofold increase in the frequency of days with very heavy precipitation (above 99.7th percentile) and a decrease in precipitation (by 20%/30 yrs) are statistically significant at the 0.05 level.

Figure 11. Regions where disproportionate changes in heavy and very heavy precipitation during the past decades were documented compared to the change in the annual and/or seasonal precipitation (Easterling et al. 2000c, substantially updated). Thresholds used to define “heavy” and “very heavy” precipitation vary by season and region. However, changes in heavy precipitation frequencies are always higher than changes in precipitation totals and, in some regions, an increase in heavy and/or very heavy precipitation occurred while no change or even a decrease in precipitation totals was observed.
Figure 12. Model simulations of the effect of CO$_2$ doubling on annual precipitation (%, top) and the average number of exceedences of the 99.7 percentile of precipitation distribution (bottom) from the HadCM3 and CGCM1 models. The red end of the scale depicts decreases and the blue increases. Changes are only shown where they are significant relative to the control climate (from archive of Hegerl et al. 2003, 2004).

Figure 13. “Consensus” estimates of changes in mean annual precipitation in the 2 x CO$_2$ experiments from CGCM1 and HadCM3 GCMs over North America. The red end of the scale depicts decreases and the blue increases. The pattern shows the average precipitation change between the models, it is only shown where the simulations with each model are consistent with the respective other model at the gridpoint level.

Figure 14. “Consensus” estimates of changes in the wettest day per year (top) and the wettest 5-day accumulation per year (bottom) precipitation in the 2 x CO$_2$ experiments from CCC and HadCM3 GCMs. (see Figure 13 for details).

Figure 15. Frequency of the upper 10% of rainy days over the northeastern quadrant of the contiguous United States. Top. Observations (Northeast and Midwest regions; Region outlined in Figure 2) for 1908-2002; adapted from Groisman et al. (2004). Bottom. ECHAM4 (35°N-45°N; 75°W-85°W; adapted from Semenov and Bengtsson 2002) 10 year running mean values for 1900-2090.

Figure 16. Number of wet days over the northeastern quadrant of the contiguous United States. Top. Observations (Northeast and Midwest regions) for 1908-2002. Bottom. ECHAM4 (35°N-45°N; 75°W-85°W; adapted from Semenov and Bengtsson 2002) 10 year running mean values for 1900-2090. Both show a decrease during the past 30 years.
Figure A1. Present coverage of North America south of 55°N with long-term (at least 25 years of data) stations. Red and blue dots show stations with ~ 100 and 80 years of data respectively. Green dots indicate stations with at least 25 years of data during the 1961-1990 period. Black dots show additional long-term Mexican stations that are presently undergoing extensive quality control.

Figure A2. Data availability over the contiguous U.S. generalized within the 1° x 1° grid cells for the periods of near-constant network. Regional partition of the country used throughout this paper for area-averaging is also shown. Count of stations with more than 50% of daily precipitation data within each grid cell for (a) the 1891-1900 (b) 1901-1910, (c) 1911-1920, and (d) 1951-2002 periods respectively.

Figure A3. Same as A2, but over the former USSR for (a) the 1901-1910 (b) 1931-1940, (c) 1941-1950, and (d) 1951-1996 periods respectively.

Figure A4. Same as A2, but over Australia for (a) the 1901-1910 (b) 1911-1920, and (c) 1951-1999 periods respectively. When creating the climate regions for the continent, we primarily used the climate zones based upon rainfall published by the Australian Bureau of Meteorology (Climate Zones according to Rainfall, http://www.bom.gov.au/lam/climate/levelthree/ausclim/zones.htm). These regions were modified somewhat using plots of the seasonal precipitation cycle and data availability considerations.

Figure A5. Same as A2, but over South Africa for (a) the 1901-1910 (b) 1921-1930, and (c) 1931-1997 periods respectively. Three climatological regions were selected by taking into account the seasonal precipitation cycle. In the eastern half of the country the precipitation
maximum is observed in austral summer (DJF) while along the Atlantic coast it is observed in winter. The desert region between the two has an annual precipitation of \( \sim 250 \) mm.

Figure A6. Same as A2, but over Brazil for (a) the 1911-1920 (b) 1941-1950, and (c) 1951-2001 periods respectively. The Nord-Este region has an autumn (MAM) precipitation maximum and two extratropical regions have a summer precipitation maximum (DJF). The southernmost region was expanded beyond the national borders to include Uruguay and adjacent small areas of Argentina and Paraguay which were also well covered by the observations in our dataset.

Figure A7. Same as A2, but over Mexico for (a) 1941-1950 and (b) 1951-2002 periods.
Table 1: Trend characteristics in share of total precipitation occurring in heavy and very heavy precipitation events over the contiguous United States, 1910-1999. Asterisks (*) indicate trends that are statistically significant at the 0.05 or higher level.

<table>
<thead>
<tr>
<th>Precipitation</th>
<th>Annual Precipitation</th>
<th>Contribution to Annual Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Value (mm)</td>
<td>Linear Trend</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Estimate (%/10yr)</td>
</tr>
<tr>
<td>Total</td>
<td>750</td>
<td>0.6 5*</td>
</tr>
<tr>
<td>Heavy (&gt; 95&lt;sup&gt;th&lt;/sup&gt; percentile)</td>
<td>195</td>
<td>1.7 12*</td>
</tr>
<tr>
<td>Very heavy (&gt;99&lt;sup&gt;th&lt;/sup&gt; percentile)</td>
<td>62</td>
<td>2.5 15*</td>
</tr>
<tr>
<td>Extreme (&gt; 99.9&lt;sup&gt;th&lt;/sup&gt; percentile)</td>
<td>12</td>
<td>3.3 11*</td>
</tr>
</tbody>
</table>
Table 2a: Trend characteristics in the number of days with heavy and very heavy precipitation over the contiguous United States, 1910-1999 (percentile definition). Asterisks (*) indicate trends that are statistically significant at the 0.05 or higher level.

<table>
<thead>
<tr>
<th>Events</th>
<th>Days with Precipitation</th>
<th>Contribution to total days with precipitation above 1mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (days / yr)</td>
<td>Linear Trend</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Estimate (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Variance (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fraction (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative Change (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Variance (%)</td>
</tr>
<tr>
<td>Total days with precipitation above 1mm</td>
<td>75</td>
<td>0.5</td>
</tr>
<tr>
<td>Heavy (above 95\textsuperscript{th} percentile)</td>
<td>4.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Very Heavy (above 99\textsuperscript{th} percentile)</td>
<td>0.88</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Table 2b: Trend characteristics in the number of days with heavy and very heavy precipitation over the contiguous United States, 1910-1999 (absolute value definition). Asterisks (*) indicate trends that are statistically significant at the 0.05 or higher level.

<table>
<thead>
<tr>
<th>Events</th>
<th>Days with Precipitation</th>
<th>Contribution to total days with precipitation above 1 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (days / yr)</td>
<td>Linear Trend</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Estimate (%/10yr)</td>
</tr>
<tr>
<td>Total days with precipitation above 1 mm</td>
<td>75</td>
<td>0.5</td>
</tr>
<tr>
<td>Heavy (above 50.8 mm)</td>
<td>1.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Very Heavy (above 101.6 mm)</td>
<td>0.13</td>
<td>4.9</td>
</tr>
</tbody>
</table>
Table 3: Trends in share of total annual precipitation occurring in heavy and very heavy precipitation events in the contiguous U.S., 1910-1970 versus 1970-1999. Asterisks (*) indicate trends that are statistically significant at the 0.05 or higher level.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (mm)</td>
<td>Linear Trend</td>
</tr>
<tr>
<td></td>
<td>Est. (%/10yr)</td>
<td>Var. (%)</td>
</tr>
<tr>
<td>Total annual precipitation</td>
<td>737</td>
<td>-0.4</td>
</tr>
<tr>
<td>Heavy (&gt; 95th percentile)</td>
<td>188</td>
<td>-0.1</td>
</tr>
<tr>
<td>Very Heavy (&gt; 99th percentile)</td>
<td>59</td>
<td>0.9</td>
</tr>
<tr>
<td>Extreme (&gt; 99.9th percentile)</td>
<td>12</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Table 4. Area-averaged annual and seasonal daily precipitation thresholds (in mm) for “very heavy” (upper 0.3%), and “extreme” (upper 0.1%) precipitation events in different regions of the contiguous United States. Note that at each specific location the threshold precipitation value may be different. The return period for such events varies depending upon the frequency of days with measurable precipitation and varies, for example, from 3 to 5 years for annual and 10 to 20 years for seasonal “very heavy” precipitation events. Region numbers correspond to those shown in Figure 2.

<table>
<thead>
<tr>
<th>Sub-region</th>
<th>Area, $10^3$ km$^2$</th>
<th>Annual</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Northwest</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>2 Missouri River Basin</td>
<td>660</td>
<td>45</td>
<td>55</td>
<td>45</td>
<td>35</td>
<td>35</td>
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<td>3 Upper Mississippi</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>4 Northeast</td>
<td>1240</td>
<td>50</td>
<td>65</td>
<td>20</td>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>5 California &amp; Nevada</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Southwest</td>
<td>680</td>
<td>65</td>
<td>80</td>
<td>30</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>7 South</td>
<td>480</td>
<td>65</td>
<td>80</td>
<td>50</td>
<td>55</td>
<td>75</td>
</tr>
<tr>
<td>8 California &amp; Nevada</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>9 Midwest</td>
<td>720</td>
<td>65</td>
<td>80</td>
<td>65</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>10 Southeast</td>
<td>1120</td>
<td>45</td>
<td>55</td>
<td>30</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>48-states average</td>
<td>8,000</td>
<td>105</td>
<td>130</td>
<td>65</td>
<td>95</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 5. Trend characteristics of the annual precipitation for the western part of the former USSR over the period 1936-1997. Trend values statistically significant at the 0.05 level or at the 0.01 level are marked with asterisks (*) and double asterisks (**) respectively.

<table>
<thead>
<tr>
<th>Precipitation</th>
<th>Totals, mm</th>
<th>Thresholds, %</th>
<th>Linear trend and its variance, %/100yr</th>
<th>%</th>
</tr>
</thead>
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<tr>
<td>North of European Russia (north of 60ºN)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>560</td>
<td>0</td>
<td>17</td>
<td>11**</td>
</tr>
<tr>
<td>Heavy, 90%-ile</td>
<td>240</td>
<td>7</td>
<td>27</td>
<td>14**</td>
</tr>
<tr>
<td></td>
<td>95%-ile</td>
<td>160</td>
<td>26</td>
<td>9*</td>
</tr>
<tr>
<td>Very heavy, 99%-ile</td>
<td>55</td>
<td>20</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>99.7%-ile</td>
<td>23</td>
<td>44</td>
<td>4</td>
</tr>
<tr>
<td>Extreme, 99.9%-ile</td>
<td>10</td>
<td>35</td>
<td>52</td>
<td>3</td>
</tr>
</tbody>
</table>

South of the European part of the fUSSR (south of 55ºN)

| Total         | 540        | 0             | 24                                     | 18** |
| Heavy, 90%-ile | 240        | 9             | 29                                     | 15** |
|             | 95%-ile    | 160           | 29                                     | 14** |
| Very heavy, 99%-ile | 55        | 25            | 40                                     | 15** |
|            | 99.7%-ile  | 22            | 20                                     | 2    |
| Extreme, 99.9%-ile | 10        | 45            | 50                                     | 10*  |
Table 6. Heavy and very heavy annual precipitation along the northwestern coast of North America. Values of mean annual precipitation, area-averaged thresholds for heavy (upper 5 percentile) and very heavy (upper 0.3%) are shown. Trend estimates in total precipitation and annual number of days above the two thresholds are also presented. Trend values statistically significant at the 0.05 level or at the 0.01 level are marked with asterisks (*) and double asterisks (**) respectively.

<table>
<thead>
<tr>
<th>Region, Period assessed</th>
<th>Total precipitation</th>
<th>95%-ile threshold</th>
<th>99.7%-ile threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Trend</td>
<td>Value Trend</td>
<td>Value Trend</td>
</tr>
<tr>
<td></td>
<td>Mm %/50yr</td>
<td>mm %/50 yr</td>
<td>mm %/50 yr</td>
</tr>
<tr>
<td>British Columbia,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>south of 55º N 1910-2001</td>
<td>1,625</td>
<td>26</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>7.2**</td>
<td>16**</td>
<td>19**</td>
</tr>
<tr>
<td>Alaska, south of 62º N</td>
<td>1,640</td>
<td>28</td>
<td>66</td>
</tr>
<tr>
<td>1950-2002</td>
<td>10.3*</td>
<td>18*</td>
<td>37</td>
</tr>
</tbody>
</table>
Table A1. Parameters of statistical structure of the fields of regional frequency of heavy (above the upper 10\textsuperscript{th} percentile) and very heavy (above the upper 0.3\textsuperscript{th} percentile) seasonal precipitation events over the contiguous United States and the European part of the former Soviet Union. Parameters of the spatial correlation function in Eq. 2 ($\rho_0$ and $C_0$) and variance coefficient, $C_v$, of the 1-degree-grid-cell-averaged values of the frequencies are presented.

<table>
<thead>
<tr>
<th>Region</th>
<th>Season</th>
<th>Events</th>
<th>$\rho_0$, km</th>
<th>$C_0$</th>
<th>$C_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA, Northwest</td>
<td>Winter</td>
<td>Heavy</td>
<td>505</td>
<td>0.85</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td></td>
<td>325</td>
<td>0.85</td>
<td>0.20</td>
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<td>Winter</td>
<td>Very heavy</td>
<td>250</td>
<td>0.55</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td></td>
<td>160</td>
<td>0.65</td>
<td>0.45</td>
</tr>
<tr>
<td>USA, Southwest</td>
<td>Winter</td>
<td>Heavy</td>
<td>300</td>
<td>0.90</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td></td>
<td>255</td>
<td>0.90</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>Very heavy</td>
<td>125</td>
<td>0.70</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td></td>
<td>95</td>
<td>0.65</td>
<td>0.30</td>
</tr>
<tr>
<td>USA, Midwest</td>
<td>Summer</td>
<td>Heavy</td>
<td>190</td>
<td>1.00</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td></td>
<td>300</td>
<td>1.00</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>Very heavy</td>
<td>95</td>
<td>0.65</td>
<td>0.40</td>
</tr>
<tr>
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<td>Annual</td>
<td></td>
<td>110</td>
<td>1.00</td>
<td>0.30</td>
</tr>
<tr>
<td>USA, Southeast</td>
<td>Summer</td>
<td>Heavy</td>
<td>270</td>
<td>0.75</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
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<td>420</td>
<td>0.85</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>Very heavy</td>
<td>155</td>
<td>0.55</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td></td>
<td>155</td>
<td>0.85</td>
<td>0.40</td>
</tr>
<tr>
<td>European part of Russia,</td>
<td>Summer</td>
<td>Heavy</td>
<td>265</td>
<td>0.75</td>
<td>0.20</td>
</tr>
<tr>
<td>north of 60°N, south of</td>
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<td></td>
<td>400</td>
<td>0.65</td>
<td>0.12</td>
</tr>
<tr>
<td>66.7°N</td>
<td>Summer</td>
<td>Very heavy</td>
<td>135</td>
<td>0.30</td>
<td>0.55</td>
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<tr>
<td></td>
<td>Annual</td>
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<td>215</td>
<td>0.30</td>
<td>0.30</td>
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<tr>
<td>European part of the</td>
<td>Summer</td>
<td>Heavy</td>
<td>275</td>
<td>0.70</td>
<td>0.15</td>
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<tr>
<td>former USSR, south of</td>
<td>Annual</td>
<td></td>
<td>400</td>
<td>0.75</td>
<td>0.12</td>
</tr>
<tr>
<td>60°N</td>
<td>Summer</td>
<td>Very heavy</td>
<td>200</td>
<td>0.15</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td></td>
<td>135</td>
<td>0.40</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Figure 1. Map of stations with daily precipitation available at the U.S. National Climatic Data Center (as of July 15, 2003). A subset of ~32,000 is available through Global Daily Climatology Network, GDCN, Version 1.0 (NCDC 2002; red dots).

Figure 2. Regions of the contiguous United States (dark-shaded) where statistically significant annual increases in very heavy precipitation for the 1908-2002 period were reported by Groisman et al. (2004).
Figure 3. Annual, heavy, and very heavy precipitation totals over the western half of the former USSR (regions of area-averaging are shown in the maps above the plots). The number of 1°x1° grid cells with valid station data are shown by dotted red lines.

Figure 4. (a) Data availability at the 88 stations over Scandinavia generalized within the 1° x 1° grid cells and (b) annual totals and frequency of very heavy annual and summer precipitation events during the 1951-2002 period. All linear trends are statistically significant at the 0.01 level or above. All increases have occurred in the past 25 years. The average regional upper 0.3% thresholds are 50 and 45 mm for summer and year respectively.
Figure 5. Heavy and very heavy annual precipitation along the northwestern coast of North America. The number of 1°x1° grid cells with valid station data are shown by red lines.

Figure 6. Annual precipitation and frequency of very heavy precipitation over southeastern and southwestern Australia (regions of area-averaging are shown in the map). The linear trend estimates are statistically significant at the 0.05 level (red) and 0.10 (blue) levels respectively.

Figure 7. Annual and summer (DJF) rainfall and frequency of very heavy rains over the Eastern half of South Africa (region of area-averaging is shown in the map). The linear trend estimate for an increase in the annual frequency of very heavy precipitation (44%/100 yrs) is statistically significant at the 0.05 level.
Figure 8. Annual rainfall and frequency of very heavy rains over three regions in Brazil, Uruguay and adjacent Argentinean and Paraguayan areas (regions are dark-colored in the map). Linear trend estimates for increases in the annual frequency of very heavy precipitation in Nordeste (1911-2001) and Northern Subtropics (1941-2001). Trends are statistically significant at the 0.05 level or higher.

Figure 9. Very heavy precipitation over regions of the Central United States shown in Figure 2. All trends indicated in the graph (even for the last three decades) are statistically significant at the 0.05 level or higher.
Figure 10. Mexico, Central Plateau (region is shown in the map). Summer precipitation and number of days with heavy (above 90th and 95th percentile) and very heavy (above 99th and 99.7th percentile) precipitation. Since 1970, more than twofold increase in the frequency of days with very heavy precipitation (above 99.7th percentile) and a decrease in precipitation (by 20%/30 yrs) are statistically significant at the 0.05 level.

Figure 11. Regions where disproportionate changes in heavy and very heavy precipitation during the past decades were documented compared to the change in the annual and/or seasonal precipitation (Easterling et al. 2000c, substantially updated). Thresholds used to define “heavy” and “very heavy” precipitation vary by season and region. However, changes in heavy precipitation frequencies are always higher than changes in precipitation totals and, in some regions, an increase in heavy and/or very heavy precipitation occurred while no change or even a decrease in precipitation totals was observed.
Figure 12. Model simulations of the effect of CO₂ doubling on annual precipitation (%, top) and the average number of exceedences of the 99.7 percentile of precipitation distribution (bottom) from the HadCM3 and CGCM1 models. The red end of the scale depicts decreases and the blue increases. Changes are only shown where they are significant relative to the control climate (from archive of Hegerl et al. 2003, 2004).
Figure 13. “Consensus” estimates of changes in mean annual precipitation in the 2 x CO$_2$ experiments from CGCM1 and HadCM3 GCMs over North America. The red end of the scale depicts decreases and the blue increases. The pattern shows the average precipitation change between the models, it is only shown where the simulations with each model are consistent with the respective other model at the gridpoint level.
Figure 14. “Consensus” estimates of changes in the wettest day per year (top) and the wettest 5-day accumulation per year (bottom) precipitation in the 2 x CO₂ experiments from CCC and HadCM3 GCMs. (see Figure 13 for details).
Figure 15. Frequency of the upper 10% of rainy days over the northeastern quadrant of the contiguous United States. Top. Observations (Northeast and Midwest regions) for 1908-2002. Bottom. ECHAM4 (35N-45N; 75W-85W; adapted from Semenov and Bengtsson 2002) 10 year running mean values for 1900-2090.
Figure 16. Number of wet days over the northeastern quadrant of the contiguous United States. Top. Observations (Northeast and Midwest regions) for 1908-2002. Bottom. ECHAM4 (35N-45N; 75W-85W; adapted from Semenov and Bengtsson 2002) 10 year running mean values for 1900-2090. Both show a decrease during the past 30 years.
Figure A1. Present coverage of North America south of 55 N with long-term (at least 25 years of data) stations. Red and blue dots show stations with ~ 100 and 80 years of data respectively. Green dots indicate stations with at least 25 years of data during the 1961-1990 period. Black dots show additional long-term Mexican stations that are presently undergoing extensive quality control.

Figure A2. Data availability over the contiguous U.S. generalized within the 1° x 1° grid cells for the periods of near-constant network. Regional partition of the country used throughout this paper for area-averaging is also shown. Count of stations with more than 50% of daily precipitation data within each grid cell for (a) the 1891-1900 (b) 1901-1910, (c) 1911-1920, and (d) 1951-2002 periods respectively.
Figure A3. Same as A2, but over the former USSR for (a) the 1901-1910 (b) 1931-1940, (c) 1941-1950, and (d) 1951-1996 periods respectively.

Figure A4. Same as A2, but over Australia for (a) the 1901-1910 (b) 1911-1920, and (c) 1951-1999 periods respectively. When creating the climate regions for the continent, we primarily used the climate zones based upon rainfall published by the Australian Bureau of Meteorology (Climate Zones according to Rainfall, [link](http://www.bom.gov.au/lam/climate/levelthree/ausclim/zones.htm)). These regions were modified somewhat using plots of the seasonal precipitation cycle and data availability considerations.
Figure A5. Same as A2, but over South Africa for (a) the 1901-1910 (b) 1921-1930, and (c) 1931-1997 periods respectively. Three climatological regions were selected by taking into account the seasonal precipitation cycle. In the eastern half of the country the precipitation maximum is observed in austral summer (DJF) while along the Atlantic coast it is observed in winter. The desert region between the two has an annual precipitation of ~ 250 mm.

Figure A6. Same as A2, but over Brazil for (a) the 1911-1920 (b) 1941-1950, and (c) 1951-2001 periods respectively. The Nord-Este region has an autumn (MAM) precipitation maximum and two extratropical regions have a summer precipitation maximum (DJF). The southernmost region was expanded beyond the national borders to include Uruguay and adjacent small areas of Argentina and Paraguay which were also well covered by the observations in our dataset.

Figure A7. Same as A2, but over Mexico for (a) 1941-1950 and (b) 1951-2002 periods.