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Editor-in-Chief: Roger Pielke Sr.

Editor in charge of Part 5 of the Encyclopedia: Faisal Hossain

Chapter 5.1 "Recent trends in regional and global intense precipitation patterns"

Pavel Ya. Groisman, Richard W. Knight, and Olga G. Zolina

5.1.1. Introduction

The term "extreme" has two meanings, one of them is purely mathematical; for example when we have a sample X(i), (i=1,2, …n) from an arbitrary distribution and the sample size is sufficiently large, the values at the distribution's upper tail more and more closely (asymptotically) follow the specific, narrow defined sets of distributions defined by the extreme value theory (cf., Coles 2001). Furthermore, the absence of precipitation (P) is quite common and under extremes at the low end of its distribution, we include prolonged intervals without P (including miniscule values) that are "sufficiently rare". Values at the tail of the probability distribution technically qualify to be considered as "extremes". However, there is no common agreement as to how far from the center of this distribution the "extremes" lie. The definition of "extreme" may well depend on the scientific, social, political, engineering, etc. application in order to evaluate the size of the "extreme" we are looking for. Upper 5% of daily events, maximum annual value, etc. were frequently used in theoretical climatological assessments (e.g., IPCC 2007), but in other areas (e.g., in hydrology, in civil engineering, in studying natural and anthropogenic hazards) the term "extremes" has a *negative* connotation. It is more widely used to describe situations that cause damage that must be prevented, mitigated and/or accounted for in long-term planning such as construction of houses, bridges, other infrastructure, human health protection, and water management. Therefore, another definition of the extreme precipitation term is "human—defined". Nature knows no bad weather, but we as a society do. Each weather event that affects societal well-being (human health, harvest, flood, drought, water supply, property value, and infrastructure) we use to consider as an extreme event. For the upper tail, the "human defined" sibling of the extreme term, drought, is measured by its impact on society and the environment.

While two approaches to introduction of the term "extreme" are intertwined and coincide at the very end of the tails of precipitation distribution, different segments of the scientific community may focus on the term differently which can cause confusion and/or misunderstanding. Some typical examples:

A two-inch daily rainfall event in the US Midwest might be categorized as "extreme", but under most circumstances a farmer would be grateful for this rainfall in the early summer.

Classification of the upper 5% (or similar percentile) of rainy days as "extremes" may be troublesome. For some, an "extreme" connotes a sense of emergency which may convey an inappropriate response.

These are legitimate concerns that warn "pure" scientists not to juggle with the words but provide responsible answers on the topic that is of high-impact practical importance. Therefore, quite early when climatologists begin talking about increases in the high end of precipitation distribution (both frequency and intensity) they will use more neutral terms, heavy, very heavy, and intense rain events (cf., Groisman et al. 2001). The term "extreme rain event" was left to the events that would undoubtly cause damage (e.g., rainfall of 150 mm d^{-1} or above). Not everyone accepted these terms though. Moreover, not everybody was happy when instead of a selection between two categories, "average" and "extreme", more sophisticated gradations were introduced that in addition vary between the research teams and regionally.

There is no way to avoid definitions of intense, heavy, very heavy, and extreme precipitation. Throughout this chapter we shall use several of them because these definitions (a) are regionally specific and (b) we are reviewing the results of different authors. We combine these definitions in Table 5.1.1 and each time when using these vague terms will clarify which definition was used and why.

There are two major types of definitions for the upper end of precipitation distribution. They can be partitioned in two classes associated with fixed thresholds (when a precipitation event is assigned to a particular class according to its absolute value, e.g., above 100 mm d^{-1}) and percentile defined thresholds (when precipitation event is assigned to a particular class according to the frequency of its occurrence (e.g., once in 10 years or in the upper 1% of rain events, etc.). There are pro and contra reasons for selection of both types of thresholds. By selecting fixed thresholds for heavy precipitation of various intensities within a region, we initiate a pre-selection of locations where the micrometeorological conditions induce these events to be more frequent. Examples are sites located on windward slopes versus the leeward slopes, coastal regions versus the inland sites, etc. In extreme cases (which are exactly a target of our assessment), we may unintentionally include only a few locations where extreme precipitation occurs due to a combination of orography and atmospheric circulation causes (e.g., Yakutat, Alaska; foothills of the Himalaya Mountains). These results when regionally averaged do not represent the entire region but only its most humid areas. But, why is it worthwhile to look for extremes in the places where they do not (or are less likely to) occur? Using the percentile thresholds that are crafted individually for each location, we (with an additional help of a carefully selected area-averaging procedure) receive a much better spatial representativeness for each region that accounts equally for precipitation extremes, for example, west and eastward of the Cascade Range in the Washington State. The last example clearly identifies one of the problems of the percentile approach: *it levels quantitatively disastrous and moderate precipitation events* which may negatively impact hydrological estimates of consequences of intense rainfall over the rough terrain (even while the places that are used to huge precipitation events may have an infrastructure that is designed to take it). The second problem with the percentile approach, when we are looking for "real" extremes, is a low accuracy of individual threshold estimates at the far end of the tail of the empirical distribution. At the right-side tail, the ranked time series provide a broad range of neighboring values that may differ from each other by scores of millimeters. Thus, the estimated "threshold" carries with it both a peculiarity of the individual observing period at the site and a large random error of the estimate.

The discussion above suggests that by bypassing the percentile estimates one can be better off by avoiding these two hidden caveats (leveling and low accuracy of the variables that are used only at an intermediate step of assessment). In the past, we experimented with and used both types of precipitation thresholds. In our opinion the upper 5% of daily precipitation events (that across the conterminous U.S. on average occur 20 times per year and bring about 30% of annual precipitation totals) and/or a mean peak annual precipitation event do not qualify for the definition of "extremes". That is why ten years ago we began using more neutral terminology "heavy", very heavy" and "intense" precipitation (cf., Groisman et al. 2001, 2005). The current concern is the possible changes in "real" extremes, i.e., those that do endanger human life and/or wellbeing. These extremes are associated with very rare precipitation events.

We also have to admit that the ongoing (and projected) changes in precipitation do not fit simplistic scales when density distribution functions (normal distribution for temperature or gamma-distribution for precipitation) shift unchanged to the left or to the right with climatic change and interpretation of "increased/decreased" areas under the tail parts of these distributions are interpreted as extreme precipitation patterns changes. These changes have been non-linear in many parts of the world. For example, (a) the increase of totals and the events frequency of at the high end of precipitation distribution may be accompanied with a decrease in precipitation totals (cf., Easterling et al. 2000; Sun and Groisman 2000; Figure 5.1.1, top); (b) interseasonal precipitation events distribution can change its grouping (Zolina et al. 2010, 2012, Figure 5.1.1, bottom; Groisman and Knight 2007, 2008); (c) changes in intense precipitation of different genera can have different directions and rates (cf., Kunkel et al. 2012a; Figure 5.1.2)[3]; and finally (d) within the high end of precipitation distribution different sign of changes can be observed (cf., Figure 5.1.3)[1].

Frozen precipitation is critically important for the land surface hydrological cycle delivering a delayed (after snowmelt) contribution to runoff. In many parts of the extratropics and in the mountainous regions, intense snowmelt represents a major source of spring extreme events (floods). It is not important how it was accumulated throughout the cold season (daily or in a few extreme snow storms). Only the snow water equivalent remaining in the spring snowpack matters. Additionally, interruptions to transportation and other aspects of everyday human life in the regions of unstable and/or ephemeral seasonal snow cover can depend upon a snowfall deficiency. Therefore, extreme prolonged no-precipitation intervals in the cold season are of less consequence as compared to the warm season. In the warm season, prolonged intervals without rain affect the entire biosphere and several critical aspects of human activity (agriculture, water consumption, river transportation and hydropower production to mention a few). Moreover, in the warm season in the extratropics, prolonged no-rain periods correspond to anomalously high surface air temperatures due to developing of the soil moisture deficit and suppressed evapotranspiration. Together, rain deficit and hotter temperature feed back to each other strengthening the hardship of the drought conditions (Meshcherskaya et al 1996, 2011;

[1] These two figures as well as three following Figures 5.1.16, 5.118, and 5.1.19 requires a more detailed explanation as to how they were originated. At all stations, we selected only days (events) with intense precipitation (as defined above). Groisman et al. (2012) sorted these events and grouped them within seven intensity ranges. Thereafter, all intense precipitation data within each daily or multi-day intensity range were summed, along with the correspondent peak hour intensity, number of days, and number of hours with non-zero precipitation during these days. From these tallies we calculated mean precipitation duration, mean daily, and maximum hourly intensity for the days (events) with precipitation for each intensity category. The same approach was applied to subsets of data for (a) the first 31 years and the last 31 years of our sample, (b) the warmest 31 years and the coolest 31 years during the 1948-2009 period using the mean annual surface air temperature of the Northern Hemisphere (TNH), of the CONUS, of the Central United States (T_{CUS}), and of the Gulf of Mexico (T_{Gulf}) as guidance, (c) intense precipitation derived from tropical cyclones (TC) in the hurricane season (June through November) and intense precipitation that originated without direct TC impact, (d) intense precipitation during various phases of the ENSO cycle (El Niño, Neutral, and La Niña months), and (e) various other combinations and complements, e.g., warmest years versus coolest years for TC-originated precipitation and, separately for precipitation that was not originated from TCs, warmest years versus coolest years only for the hurricane-free season, warm season (May-October) temperatures for T_{CUS} and T_{Gulf}, minimum and maximum temperatures for T_{CUS}, etc. This approach generated a suite of estimates of climatology and changes with time, global and regional temperatures, rainfall genera, ENSO, etc., of intense precipitation events.

Barriopedro et al. 2011, Dai et al. 2004; USCCSP 2009). We shall describe the changes in the no-rain periods duration in **5.1.3e** sub-section.

[BOX INSERT] ***Cautious note.*** Here, we outline an important feature of combination of increase in both frequencies, in prolonged no-rain intervals and intense rainfall. Quite often hydrologists and climatologists use *dynamic* characteristics of heavy/high rain/streamflow events such as annual maximum of daily rainfall (or peak streamflow). If these characteristics show systematic changes (trends) they claim an increase in heavy (or extreme) precipitation and streamflow. If these characteristics do not have trends, they argue that nothing has been changed, e.g., with flood frequency (cf., Lins and Slack 1999; Hirsch and Ryberg 2011). However, in the regions where both ends of the precipitation (streamflow) distribution are affected, we can observe a high flow (rainfall total) year followed by low flow (rainfall total) year and maximum annual rainfall or peak streamflow (as well as any *dynamically* defined characteristic of the distributions tail based upon the data of a single year) will vary widely without showing systematic changes. In Sub-section **5.1.3** we show that this is the case in some regions of the world (including the eastern part of the contiguous U.S.; cf., also Semenov and Bengtsson 2002). **[END OF THE BOX INSERT]**

Daily data are the most widely available for analyses (cf., Global Historical Climatology Network-Daily, http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/)). However, there is no reason to focus on single-day events only because intense precipitation events, except small-scale convective thunderstorms, have longer time scales. Even a short-term rain while beginning before the cessation time (which in many countries is not necessarily at midnight) can continue beyond this time, creating an impression that this is a two-day long event. To remedy this problem, different options were considered in studies of intense precipitation change. These include (a) consideration of 2-day (up to 5-day-long) rainfall totals (Kunkel et al. 1999, 2012a,b; Groisman et al. 2001; Alexander et al. 2006); (b) a thorough documentation of the actual hours of begin and end of the rain events (Bonnin et al. 2004-2012); (c) assessment of the frequency of consecutive precipitation days (wet spells; Zolina et al. 2010, 2012) and consecutive intense rain days (intense rain events; Groisman et al. 2012); and (d) assessment of sequences of deep cyclones that one after another cross the region in a short time interval (e.g., in 2 to 3 weeks) with intense rains associated with them that first saturate soil, and later fill all water bodies eventually causing disastrous floods (Lettenmaier et al. 2008; Kunkel et al. 2012b).

In the next Sections we present an outline of the theoretical background behind expected changes in heavy and extreme precipitation (Sub-section **5.1.2**) and the observed changes in extreme precipitation during the past 50 years over the global land areas (Sub-section **5.1.3**). To document "observed" changes in rare precipitation events (extreme precipitation), one has to rely upon dense networks of many thousands of stations with long-term daily and hourly precipitation time series. However, these networks do not exist (or are not available to us) in some parts of the world. Therefore, saying changes over "global land" we shall focus mostly on the extratropical land areas that are better covered by observations and on the regions/nations that share openly their data sets with the international scientific community. For some countries (e.g., for China, South Africa, and Japan), we are still able do our assessment using findings of national climatologists and hydrologists who have unrestricted access to the richest national hydrometeorological archives (cf., Zhang et al. 2011). For other countries (e.g., Poland) the international data centers either have no access to the volumetric national meteorological data or the national climatologists do not have permission to view and assess the complete daily data of the national hydrometeorological archive. Therefore we had to omit the territories of these countries from consideration.

5.1.2. Theoretical background behind expected changes in extreme precipitation

a) Common sense consideration associated with warmer climates (and global warming)

Climatologists used to look at the changes in extreme precipitation events (especially on the changes of prolonged extreme events such as droughts and perennial rainfall), in the dynamic Earth system "memory" that includes anomalies in sea ice (SI) and snow cover extents (SCE), sea surface temperature (SST), soil moisture and the water holding capacity of the atmosphere above the region, and their patterns (e.g., Southern Oscillation; North Atlantic Oscillation,. etc). However the major "memory" component of the Earth system is the Earth Climate System itself. It began changing (Figure 5.1.4; IPCC 2007) and is no longer a constant factor: SST, SI, and SCE anomalies of the past now became "climatology" (cf., Figure 5.1.4) and it is time to include this new reality in our analyses of the frequency and intensity of extreme events.

The two-sided impact of the global temperature change on the water cycle was best expressed by Kevin Trenberth (2011): "There is a direct influence of global warming on precipitation. Increased heating leads to greater evaporation and thus surface drying, thereby increasing the intensity and duration of drought. However, the water holding capacity of air increases by about 7% per 1°C warming, which leads to increased water vapor in the atmosphere. Hence, storms, whether individual thunderstorms, extratropical rain or snow storms, or tropical cyclones, supplied with increased moisture, produce more intense precipitation events". Everything else is details. However, these details are worth discussing especially because we want to see the evidence of these changes.

The global warming (currently more than 1°C and most of it has occurred in the last 50 years) is most pronounced in the high latitudes and in the cold season. "Greater evaporation" (ablation) from snow and ice cover is not the strongest source of additional water vapor to the atmosphere and definitely will not cause surface drying and or droughts. Also, 70% of the globe (with sea and land ice areas even more) will not "dry" when more evaporation occurs. Also, what difference will it make if the downpours will be stronger over the oceans? Large land areas in mid-latitudes of North America and Eurasia up to the last two-three decades had resisted warming in summer. In other words, summer surface air temperatures there had not notably changed (no summer warming trends) and thus no surface drying[2].

The water holding capacity of the atmosphere has increased in the last decades (cf., Seidel 2002; Santer et al. 2007; Schneider et al. 2010). Therefore, there are good reasons to expect that occasionally, when other pre-conditions are right, the atmosphere may deliver downpours instead of usual rainfall. However, this "common sense" reasoning meets a couple of arguments:

The atmosphere over the Sahara Desert holds a lot of water but obviously remains insufficient for rainfall; and

What if these "other pre-conditions" are changing in the other direction (e.g., occurring less frequently) and/or their ability to promote extra-rain has already been exhausted. The last argument can be illustrated by the following observations based on the North American Regional Reanalysis (Messinger et al. 2006). While the nationwide number of days with maximum daily

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[2] This situation has been changed in the last few decades (cf., Figures 5.17 and 5.1.22 below; Roshydromet 2008; Blanden et al. 2011; and IPCC 2007)

convective available potential energy (CAPE) above 1500 J kg^{-1} over the conterminous United States in spring has increased by 30% during the past three decades, it did not change in summer and actually decreased over the Southwestern U.S. in the Four Corners States (cf., Figure 5.1.5). There is climatological evidence that in warmer climates precipitation intensity distribution shifts toward higher daily totals and this shift occurs around 25-30 mm. Frequency of rain days with P below this threshold decreases with warmer temperatures and the frequency of rain days with P above this threshold goes up (Karl and Trenberth 2003). This indicates that intense precipitation frequency changes might be inhomogeneous by intensity, and in the warmer climate "moderately intense" rain events may remain intact or even decrease (cf., Figure 5.1.3; Groisman et al. 2012). In wet tropics, the days with 25-30 mm rainfall cannot be considered as extremes. In high latitudes and in dry climates of the mid-latitudes, the occurrence of these days is already very rare. Over CONUS, the days with precipitation below 25.4 mm deliver about 65% of annual totals and comprise about 95% of the days with non-zero rainfall. The last number means that over CONUS, the analyses of the changes in "the upper 10% of days with precipitation" do not have to increase with global warming[3] if we rely upon the Karl and Trenberth (2003) findings, but the higher percentiles should be considered to reveal signals in heavy and very heavy precipitation associated with global warming (cf., further Sub-section **5.1.3**). On the other hand, if climatological considerations leave 95% of rain days without "the necessary impetus to increase" with global warming, other factors may affect the occurrence of these days. Leaving the changes in the atmospheric circulation aside (we shall discuss them later), let us mention here the increase of the duration of the warm season, more winter thaws and earlier snowmelt, and the regional warming (especially in the shoulder seasons, spring and autumn). All these factors have been already documented for the northern extratropics (ACIA 2005; Alexander et al. 2006; IPCC 2007; Groisman al Soja 2009; USCCSP 2009; Walsh et al. 2011; Callaghan et al. 2011a,b). They tend to promote the warm season water deficit, feed back to the atmosphere over the land by reduction of the latent heat flux and tropospheric relative humidity, and decrease the number days with rain in the mid-latitudes. Theoretical (based on the GCM projections) conclusions that this might be the case were made by Manabe et al. (1981, 2004); Semenov and Bengtsson (2002); and Barriopedro et al. (2011). Dai et al. 1998, 2004), Groisman and Knight (2007, 2008); Groisman et al. (2009); Zolina et al. (2012) which all showed that this is indeed the case over many regions of the extratropics (cf., further Sub-section **5.1.3e**).

b. Changes in atmospheric circulation that can promote changes in extreme precipitation

While the moisture source of some precipitation fraction originates from land, especially in the interior areas of the continents and/or from wetlands (cf., Kuznetsova 1983, Brubacker et al. 2003), the major source of water vapor for precipitation is the World Ocean. Water vapor is advected into the land areas by atmospheric circulation and is affected by changes in the pattern of this circulation. An example is the size, frequency, strength and humidity of the transient cyclones. Generally, there are at least two ways to assess the circulation changes.

[3] For example, Michaels et al. (2004) did not take this into account and after analyzing the trends in the 10 largest annual daily rainfall totals did not find any increase over CONUS. They concluded that there are no increases of heavy precipitation over CONUS but (a) their totals in many dry regions of CONUS included a significant fraction of daily rain events that are less than 25 mm and (b) Michaels et al. used *dynamicall*y defined definitions of high rainfall (10 rain events each year) that in dry years could further drive their statistics away from the characteristic of heavy precipitation (cf., box insert in Sub-section **5.1.1**). Thus, incautious selection of statistics for analysis had led to conclusions that contradict findings of other researchers.

A *direct approach* can be used when the cyclones positions and size are documented and assessments of the macro-circulation variables – indices of climate variability (ENSO, Pacific Decadal, Arctic, and North Atlantic Oscillations, etc.) are known. Their list is conveniently provided by Blunden et al. (2011). The cyclones listed can be connected with effects which are responsible for atmospheric circulation conditions causing (or are favorable to) extreme precipitation in particular regions of the globe. With development of reanalyses (cf., Kalnay et al. 1996; Uppala et al., 2005; Compo et al. 2011), this approach became less laborious than in the past when synoptic maps were analyzed manually. Monitoring from space made it possible to document and better categorize tropical cyclone movement in the past several decades (Landsea et al. 2006). Systematic shifts in the cyclone tracks (both tropical and extratropical) bring torrential rains to the regions that have not been accustomed to them and left the regions that rely upon these cyclones for their water supply with drier conditions. For example, more frequent poleward shifts of the extratropical cyclone tracks in the Southern Hemisphere in the austral winter (June, July, August) season leave the southwestern tip of Australian continent without its major water supply. This development has already been observed (Groisman et al. 2005; Land & Water Australia, 2009) and resulted in mean and intense precipitation decrease. One of the IPCC projections (Meehl and Stocker, et al. 2007) is that poleward shifts of extratropical cyclone tracks in both hemispheres will be more probable (Yin 2005; Graff and LaCasce 2012) promising no future relief to southwestern Australia. In the Northern Hemisphere this poleward shift may mean a future increase in the cold season heavy precipitation in the Arctic and sub-Arctic regions of Europe and Asia (the development that is already observed there (Førland and Hannsen Bauer 2000; Rawlins et al. 2010).

Tropical cyclones (TC) and their extratropical remnants during the landfall are causing heavy, very heavy and extreme rainfall. After the first historical statistics of Atlantic hurricanes became available, Vetroumov (1977) showed that with the warmer hemispheric temperatures the number of hurricanes that cross 30°N moving northward increased. The origin of several unusually severe storms that hit Europe in the last two decades can be tracked to the tropics (Thorncroft and Jones, 2000; Evans and Hart 2003) and, if the relationship documented 35 years ago is still valid, we can anticipate further more frequent such visits. North Atlantic hurricanes are the most thoroughly studied tropical cyclone. The strength of the most violent landfalling hurricanes (categories 3 through 5 of the Saffir-Simpson scale with sustained wind speeds exceeding 96 knots (or 49 m s^{-1}) in the last three decades increased (Emanuel 2005; USCCSP 2009). This resulted in an increase in heavy, very heavy, and extreme precipitation over the southeastern U.S. associated with TCs (Figure 5.1.2; Kunkel et al. 2010, 2012b).

Macro-circulation variables or indices of climate variability received their names because they describe significant fractions of regional climatic variability in different parts of the Globe. Among the characteristics of this variability is precipitation (cf., Girs 1977; Ropelevsky and Halpert 1996; Becker et al. 2010) including heavy and very heavy precipitation (cf., Gershunov and Barnett 1998a; Cavazos and Rivas 2004; Haylock et al. 2006; Scaife et al. 2008; Caesar et al. 2011; Nigam et al. 2011; Lau and Kim 2012). It is very important to be able to ascribe a sizeable part of the variability of such disruptive events as intense precipitation linking it to ENSO, NAO, and other indices of climate variability. Most of these indices have memory much longer than the synoptic time scale, and thus provide guidance for seasonal projections of precipitation including its intense form. The changes of some of these indices (e.g., those that are directly related to sea surface temperature (SST), such as Pacific Decadal Oscillation, Mid-Atlantic Oscillation) can be projected assuming that their low—frequency component will *eventually* follow global warming and the SST rise. However, several major indices (namely, NAO, AO, and ENSO) have not shown systematic trends in the past century and the modern GCM projections are not confident about their future dynamics:

Being the strongest internal large-scale driver of the global climate variability, ENSO and its future is of special interest (cf., Gershunov and Barnett 1998b). A number of GCMs experiments of the climate change under the greenhouse gases forcing hint to the "El Niño-like" pattern of the future climate with continuing global warming (cf., Meehl and Washington, 1996; Kug et al. 2011) and the last IPCC assessment states that " …Multi-model averages show a weak shift towards average background conditions which may be described as 'El Niño-like', ….." (Meehl and Stocker et al. 2007). However, the same IPCC Report indicates that GCMs used for that Assessment are not coherent in projections of the future distribution of occurrences of El Niño and La Niña events (cf., Latif and Keenlyside 2009). Five years later, we hope that the new generation of GCMs participating in CMIP5 will be more confident/coherent in quantification of this future distribution so that the numerous applications can follow up with the estimates of its impact on probabilities of the extreme precipitation events occurrence worldwide.

In the northern extratropics between 35° N and 65° N, a large fraction of the moisture transport to the continents is conducted by prevailing westerlies within the Ferrel cell where air flows poleward and eastward near the surface and equatorward and westward at higher altitudes (Style 2012). The air movement in the westerlies is characterized by sequences of cyclone and anticyclone movements that in the atmospheric pressure field are seen as Rossby waves (Rossby et al. 1939; Dickinson 1978). Rossby waves provide a major mechanism for heat transfer in the atmosphere between high latitudes and tropics. With the Arctic warming being stronger than the tropics (cf., Figure 5.1.4), the meridional surface air temperature gradient has weakened (Groisman and Soja 2009), and future IPCC climate projections hint that the changes in the high latitudes will continue to be larger than in the tropics thus affecting the amount and form of meridional heat transfer in the atmosphere.

Over North America, with its exposure to the winds of southern directions and northeaster Atlantic events, the westerlies fraction is less than over Northern Eurasia which is practically insulated from atmospheric moisture transport from the tropics by mountain ranges and plateaus. Over Northern Eurasia, several indices were traditionally used to characterize stable forms of atmospheric circulation over the Northern Extratropics. Two of the most broadly used are classifications developed by Dzerdzeevsky (1975) and Wangengheim (1946) and his follower Girs (1974). According to Wangengheim classification, there are three major circulation types in the Atlantic-West Eurasian sector of the northern extratropics: western (**W**) that is characterized by unobstructed eastward movement of the atmospheric cyclones within the 35°-65°N zone over Europe and West Asia and two meridional atmospheric circulation types (**E** and **C**) that are characterized by large-scale meandering of westerlies. Days with the E-type, for example, are characterized by anticyclonic conditions over European Russia while the days with the C-type are characterized by anticyclonic conditions over Western Europe and humid conditions over the Volga River Basin in European Russia. The frequencies of the seasonal occurrence of these days over the past century changes, and in Figure 5.1.6 we present the dynamics of changes of the number of days with W- and C-types of atmospheric circulation.

During the days with W-type of atmospheric circulation the heat exchange between polar regions and tropics is weaker than usual. Figure 5.1.6 shows an increasing trend in the frequency of the W-type in the cold season, when the meridional temperature gradient has significantly decreased during the past 130 years (Groisman and Soja 2009). This allows more frequent westerlies in the cold season. Also we observe that the number of days with **C**-type of circulation has systematically decreased throughout the 20th century during the warm season. This implies a century-long increase in the warm season of the number of days with **E**-type of circulation associated with high atmospheric pressure ridge over the European part of the former USSR (in the last three decades this increase was partially balanced by the increase in the W-type days after the 1970s). Each of these circulation types has regions over Eastern Europe where precipitation was well above and/or below the long term mean values (Girs 1974). Changes in the days with circulation types and meandering of Rossby waves are a manifestation of the same feature: large-scale climatic change. Frequencies of regional intense precipitation associated with atmospheric cyclones follow these changes. Currently, to recognize the pattern of the future atmospheric circulation changes in relation to the inferred extreme precipitation changes is a subject of ongoing and future research (Schubert et al. 2011).

Currently the comprehensive assessment of Global Climate Models' projections is available in IPCC (2007; Ch. 10 and 11) but they are already 5 years old. The new crop of these projections for the next IPCC Report is currently in preparation (cf., https://www.ipcc-wg1.unibe.ch/) and is unavailable to us. It would be fair simply to cite Executive Summary from Chapter 10 (Meehl and Stocker, et al. 2007) on precipitation Extremes and Droughts: "Intensity of precipitation events is projected to increase, particularly in tropical and high latitude areas that experience increases in mean precipitation. Even in areas where mean precipitation decreases (most subtropical and mid-latitude regions), precipitation intensity is projected to increase but there will be longer periods between rainfall events. There is a tendency for drying of the mid-continental areas during summer, indicating a greater risk of droughts in those areas. Precipitation extremes increase more than that does the mean in most tropical and mid- and high-latitude areas".

Possible impact of the changing land use and land cover

Several overviews (Rauner 1972; Fedorov 1977; Kabat et al. 2004) provide vivid examples of how the surface roughness and transpiration rates different for the forested and unforested areas impact the convective processes over these areas and, therefore, the thunderstorm activity. In particular, (Pielke et al. 1997) provided theoretical calculations explaining how the replacement of the forested area (even a grove) with farmland decreases the atmospheric convection and leads to a very different frequency of convective precipitation. Let us remember that a lion's share of the mid-latitude land areas has lost its natural land cover. Some of these areas were converted into agricultural regions many centuries ago (e.g., Europe, China). In other areas, the changes are occurring right now (e.g., Amazon, Thailand, Indonesia). There are regions in Eurasia and North America where several man-made changes have occurred during the past two centuries due to industrialization, rail road construction, intense mining, post-industrial development, urbanization, deforestation, reforestation, reservoirs' construction, intensification of agriculture practice, and land abandonment. These forced changes converted more than half of the present land cover from a product of the Global Earth system (of its biosphere and climate) into a new reality where we live and have to adjust to the coming changes. The discussion of these changes resides beyond the scope of this Chapter but here we want only to note that the man-made environment is generally less sustainable than the natural ecosystems unless it is closely controlled by humans (e.g., by irrigation) and can quickly deteriorate (change) if this control stops (e.g., land abandonment, financial constraints, etc.). In the following case study we put together several arguments to demonstrate the possible impact of the changing land use and land cover on the warm season heavy rainfall and maximum temperature trends over the heartland of the conterminous U.S.

Case Study. The central U.S. with a particular focus on the Midwest

Presently, there are concerns that human activity in the central U.S. and the adjacent areas can interact and change various components of the regional water budget (cf., Segal et al. 1998; Moore and Rojstaczer 2001; Vörösmarty et al. 2004; Hossain et al. 2009; DeAngelis et al. 2010; Groisman et al. 2012).

DeAngelis et al. (2010) assessed the potential impact of increasing irrigation in the High Great Plains (the Ogallala Aquifer) on the summer precipitation over the central U.S. Analyses of the literature, process studies, modeling experiments, water vapor tracking within the Regional Reanalyses and climatic models' output made a strong case that the anthropogenic increase in evapotranspiration (ET) over the Great Plains under irrigation (just westward of the central U.S.) can lead to an increase in summer rainfall. In support to these theoretical projections, they found a 20% statistically significant increase in observed July precipitation over the region located in the center of our study area (~Midwest) for the 1950-2000 period compared to the previous 50 years.

Groisman et al. (2012) showed a relationship between regional maximum warm season temperature (T_{max}) and distribution of the intense precipitation; they are negatively correlated and T_{max} has a negative trend during the 1948-2010 period. If we assume that T_{max} changes are responsible for observed changes in regional heavy rainfall, the T_{max} decrease between the two 31 year periods is (a) insufficient to describe the observed changes in intense precipitation distribution and (b) does not explain all of the observed change in extreme rainfall in the past three decades (cf., Figure 5.1.16 in **5.1.3**; Groisman et al. 2012).

Let us consider the dynamics of changes and relationships among heavy precipitation frequency, D (here, the number of days with P> 25.4 mm), T_{max}, T_{min}, and land use in the central U.S. Upper panels in Figure 5.1.7 present maps of linear trends in May-July T_{max} and T_{min} over CONUS for the 1950-2011 and 1970-2011 periods. For summer, and for the entire warm season (April-October) the pattern of these trend estimates appears similar. A singularity of these patterns for T_{max} in the central United States and, in particular, in the Midwestern states is apparent. Correlation analysis shows that the regionally averaged warm season maximum temperatures over CONUS are negatively and statistically significant correlated with regionally averaged D. Only after impact of T_{max} is excluded, D is positively correlated with T_{min}[4]. Keeping in mind that over the central U.S. T_{min} has steadily increased during the past 60 years and its close relationship to D within the warm season after the removal of the T_{max} impact (partial correlations; not shown; cf., also Dessens 1995), one can also expect an increase in the frequency of heavy precipitation over the eastern U.S. This increase was indeed reported on numerous occasions (cf., Karl and Knight 1998; Groisman et al. 2001, 2004, 2005, 2012) and the bottom panels in Figure 5.1.7 show updated D and T_{max} time series for the Midwest. Their negative correlation manifests itself on an interannual level. After accounting for effect of D on T_{max} for both seasons, the residual time series of T_{max} show an increase by 0.6°C/63yr. This increase is in line with the nationwide trends of T_{min} and trends of T_{max} beyond the boundaries of the central US. It appears (this suggestion also requires support by regional climate model calculations instead of a bold

[4] All correlation analyses were conducted for de-trended time series of regionally averaged D, T_{max}, and T_{min}.

statement), that an impact of more frequent heavy precipitation caused the T_{max} decrease. However, what other factors could have forced D in the central U.S. to change so dramatically that it even reversed (or slowed down) the continental-wide warming? Groisman et al. (2012) speculate that the local land use and water withdrawal changes were among significant contributors trends in heavy precipitation. Their reasoning was as follows:

In the central U.S., the water cycle changes observed over the past 70 years have occurred simultaneously with changes in land use and water management (USGS 2004). Large reservoirs may significantly alter local precipitation patterns by increasing the probability of extreme rainfall as the result of intensification of the hydrological cycle through enhanced evaporation from open-water bodies (Eltahir and Bras 1996). Registered dams in the USA (~75,000 of them) are capable of storing a volume of water equaling almost one year's mean runoff of the entire nation (Graf 1999). According to the National Inventory of Dams, most of them (~40,000) were built from the mid-1940s to the end of the 1970s, many of them in the Central U.S., whereas another ~20,000 were built prior to 1945. For example, the area of large reservoirs in Illinois during the 1979-2009 period doubled compared to the previous 31 years.

In the past several decades there have been major changes in agricultural management practices in the Central United States. Among these are a near-quadrupling of plant density for maize, adoption of soybean as a major crop essentially producing a bi-culture (corn and soybean) managed ecosystem, and earlier planting dates as a result of advances in mechanization and plant breeding (Swanson and Nyankori 1979; O'Neal et al. 2005). It is conspicuous that the core area of the T_{max} decrease nearly coincides with the boundaries of the U.S. "Corn Belt". Intensification of agriculture and changing crop patterns over large areas of the Central U.S. (including the Upper Great Plains) consumes (and transpires back into the atmosphere) a significant amount of additional water requiring tapping ground water storage and intercepting and diverting runoff. Therefore, changing crop patterns and water use over large areas may feed back to the water cycle through changes in transpiration and evaporation from additional open water surfaces, thus supplying the atmosphere with additional water vapor. These feedbacks became stronger in the last decades compared to the 1948-1978 period when dams were under construction and many agriculture intensification measures were still in the planning stage. Groisman et al. (2012; their Table 3 and Figure 10) put together a few crop statistics for the Corn Belt States that illustrate the above statements. While a quantitative assessment of the land and water use dynamics over the entire Central U.S. goes well beyond the scope of this Chapter, Figure 5.1.8 further illustrate the above arguments. More than doubled total corn and soybean yield in three major producer states (Iowa, Illinois, and Indiana; tripled for Iowa soybeans) requires for its production additional water, part of which transpires to the atmosphere. For the three core US Midwestern states in Figure 5.1.8, the time series of dynamics of the states' area covered by corn and soybeans in percent of the total states area (including cities, water bodies, highways, etc.) and the harvest in liters per square meter related to the same area are presented (using the NASS data). In this figure, we converted dry bushels used in agriculture as a harvest measure into liters to make it vividly obvious what the intensive agriculture did to the regional land cover and the surface water budget. Currently, each square meter of land in these states produced about 0.5 dry liters of corn and soy beans more than 60 years ago. To generate this additional amount of bio-production, about 200 liters of water (or 200 mm of water layer) should be consumed and transpired back into the atmosphere during the vegetation period (cf., http://corn.agronomy.wisc.edu/Management/L026.aspx). Changes in the regional cloudiness and its characteristics would allow elucidating the further fate of this water but analysis of the changes in the US cloud cover during the past 15 years compared to the previous decades is not possible due to the inhomogeneity of the national cloudiness in situ observations[5]. However, additional water vapor released in the form of the latent heat flux during the day, would be sufficient to reduce the local daytime surface air temperature by several degrees Celsius[6], which can explain the observed regional temperature trends.

Increases in the areas of corn and soy beans fields within the Corn Belt were mostly at the expense of wheat fields. However, a brief check of the wheat yield in the central states of the U.S. shows that the water consumption (and thus the transpiration) here has also increased. For example, total wheat yield has increased by ~50% in Kansas, Missouri, and Oklahoma without significant changes in total field areas. In Illinois, we observe a 15% increase of the wheat yield from the fields whose area in the past three decades has become 25% less than in the three post-WWII decades.

The following analyses of regional temperature trends over the central U.S. and their relationship with D revealed that

- over Midwest during the vegetation season (May-September), a significant increase in D has been uncorrelated with T_{max} and T_{min} and
- absence of trends in the warm season T_{max} in the central U.S. during 1950-2011 period can be attributed to droughts of the 1950s (in the South, where it was replaced by increasing trends in the 1970-2011) and to a significant land use change (Midwest; Figure 5.1.8).

The local land and water use factors mentioned above may change the precipitation recycling ratio. The regional changes in intensity of the water cycle are usually quantified through the precipitation recycling ratio that describes the contribution of local evaporation to local precipitation (Eltahir and Bras 1996). Estimates made under the GEWEX Continental-scale Experiment in the Mississippi River Basin showed that recycled precipitation plays a significant role during the warm season (Brubaker et al. 2003) and vary depending on definitions and estimation methods. Trenberth (1999) estimates the annual recycling ratio for the Mississippi River Basin at 21%, and Bosilovich and Schubert (2001) reported a large inter-annual variability of this ratio between dry and wet summers. Zangvil et al. (2004) pointed to an inter-relationship between agriculture production and precipitation recycling in the region. All of the above show that rainfall recycling is a significant local source of precipitation especially in the warm season and indicates a potential for strong feedbacks of the land use and water management changes to the hydro-meteorological conditions over the Central U.S. Therefore, any external impact on water recycling (e.g., anthropogenic) can substantially change the entire regional water budget

[5] In the mid-1990s, the US National Weather Service introduced automated surface observing system (ASOS) that changed the in situ cloud cover observations (NWS 1998). These observations became incomparable with the past cloud cover data. Sun (2003) and Sun and Groisman (2004) reported an increase in the annual low cloud cover over the central U.S. for the 1949-1994 period (e.g., by 2.1% $(10\ yr)^{-1}$ for Midwest) but to expand their time series up to date is not possible.

[6] Energy required to evaporate 1 mm d^{-1} of water with the daytime temperature of 20°C is equal to 28.35 W m^{-2} that, while taken from the daytime surface energy budget (otherwise intact), could reduce the surface air temperature by up to 5 °C, if we assume that all this energy was taken from the surface radiation budget. In the real world, a part of this energy will be spent at the expense of sensible heat flux reduction. Additional water vapor in the atmosphere (a) will heat the surface due to an additional greenhouse effect, (b) if condensed into clouds, will cool the surface in the daytime, and/or (c) will be quickly transported away and will not affect the surface in the region at all. Nevertheless, an additional evapotranspiration of 200 mm during 120 days of the active crop development (up to 8 mm d^{-1} in the peak of corn silking, cf. Kranz et al. 2008) should substantially reduce the outgoing long-wave radiation and closely associated with it the surface and surface air temperatures.

and precipitation intensity distribution (cf., Stidd 1975; Avissar and Liu 1996; Sacks et al. 2008; Feddema et al. 2005; Mahmood et al. 2010). In conclusion, it is worthwhile to note that the regional land use change has already affected intense precipitation distribution in Israel (cf., Ben Gai et al. 1998).

5.1.3. Observed changes in extreme precipitation during the past 50 years over the globe

Instrumental precipitation data available and their problems

Each empirical study of extreme precipitation over a given region requires a dense network of meteorological stations (i.e., a network with high spatial resolution) with long-term precipitation time series at daily or sub-daily temporal resolution. There are several reasons for this requirement:

A small scale spatial resolution of *some* precipitation extreme events (for example, rainfall from summer thunderstorms has a typical radius of correlation of ~10 km; cf., Gandin et al. 1976). A sparse network of point measurements can easily miss the intense rainfall event or provide biased information about its peak intensity.

Duration of intense rainfall or an intense phase of the prolonged rain event may be quite short (in many cases only a few hours) and assessment of precipitation totals for longer periods, e.g., monthly totals, may miss most of the features that make extreme precipitation so dangerous by causing flash floods in both urban and natural environments (cf., Changnon and Westcott 2002; http://www.nws.noaa.gov/hic/flood_stats/Flood_loss_time_series.shtml; Villarini et al. 2009; Robinson et al. 1998; Smith 2002). Furthermore, even the most violent rainfall can follow or be preceded by prolonged dry weather conditions and thus be virtually unnoticed within the totals.

Therefore, advances in accumulation and broad dissemination of the regional datasets that possess the above mentioned properties closely correlate with our ability to document extreme precipitation events, to estimate their frequency, intensity, and changes in time and space.

As a vivid example, below we describe advances in studies of intense precipitation over the continuous U.S. during the past fifteen years. These studies used different methods and databases (Karl et al. 1997, 2009; Karl and Knight 1998; Easterling et al. 2000; Kunkel et al. 2003, 2007, 2010, 2012a; Groisman et al. 1999, 2001, 2004, 2005; USCCSP 2009). The common feature in these data sets was the aggregation of precipitation to daily totals because initially, there were no other reliable sources of climatological information on precipitation changes. US Historical Climatology Network (that included initially 182 stations with daily data (now more than 1200 stations, http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html) was used by Karl and Knight (1998), Groisman et al. (1999), and Easterling et al. (2000) to assess the upper 5th percentile of stations' daily totals, the number of days with precipitation above 50.8 mm, and the changes in parameters of precipitation distribution with time. When the major archive of daily cooperative (COOP) stations was updated backwards from 1948, the U.S. climatologists were able to employ about 6000 daily time series over the US and assess the century-long changes in very heavy precipitation events (in the upper 0.3% percentile of the precipitation distribution; cf., Groisman et al. 2004, 2005, USCCSP 2009). At each step, the advance was defined by new digital data sets of scientific quality that became available at that time and societal demand fuelled by accelerated climatic changes and GCMs projections. The current concern is the possible changes in "real" extremes, i.e., those that do endanger human life and/or wellbeing. These extremes are associated with very rare precipitation events. For example, days with rainfall totals above 154.9 mm over the Hourly Precipitation Data (HPD) stations of the contiguous U.S. occurred once per 60 years and over the U.S. Midwestern states, once per 135 years. Using two independent precipitation data sets (HPD and COOP) and using the data only after World War II (which are much more numerous), it became possible to analyze the changes in the occurrence of these extreme events (Groisman et al. 2012).

Precipitation is the most closely monitored meteorological variable. The authors of the World Water Balance Assessment (WWB 1974) used climatological data from more than 100,000 individual rain gauge sites for their Assessment. At that time, focus was on monthly and longer time scales (cf., Legates 1987) and to date, the major international Center for Precipitation data dissemination, Global Precipitation Climatology Center (GPCC; Beck et al. 2005; http://gpcc.dwd.de/), archives and disseminates only the monthly precipitation data of approximately 45,000 stations. These data are disseminated in the gridded format due to restrictions imposed by the National Weather Services. Due to these restrictions present up to the last decade, daily data were infrequently used for large scale precipitation change studies beyond the national boundaries. They remained preserved in different national archives worldwide. Since that time, attempts to assess precipitation changes at the daily and/or sub-daily time scales still have to rely on much smaller data collections. For example, the German and Mexican national archives store precipitation data from more than 7000 and 6000 stations respectively, but they have not yet been tapped for international climate change assessments. For other nations the situation is similar. An attempt to change this situation was launched several years ago with establishment of the Global Historical Climatology Network-Daily (GHCN-Daily). Figure 5.1.9 shows the map of the meteorological stations density available in GHCN-Daily data collection for the past 60 years. This data set inherited all daily precipitation information available in the United States, Canada, and Australia as well as several other national archives. The densest historical station networks come from the United States, Canada and Australia -- a reflection of the comprehensive contributions from these countries to GHCN-Daily. Nevertheless, Brazil, India, and South Africa have also contributed records from very dense national precipitation networks. For Europe, Russia, and China the network contains only the stations designated for the international exchange by the national meteorological services of these countries.

GHCN-Daily is comprised of daily climate records from numerous sources that have been integrated and subjected to a common suite of quality assurance reviews (http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/). The data set contains records from over 75000 stations in 180 countries and territories. Numerous daily variables are provided, including maximum and minimum temperature, total daily precipitation, snowfall, and snow depth; however, about two thirds of the stations report precipitation only. The GHCN-Daily dataset is regularly reconstructed (usually every weekend) from its 20-plus data source components to ensure that GHCN-Daily is generally in sync with its growing list of constituent sources. During this process, quality assurance checks are applied to the full dataset. The interval covered by GHCN-Daily station records varies from less than one year up to over 175 years, with the average precipitation record lasting about 33 years. The updates are conducted routinely but with delays for most of the globe except the contiguous United States. The European, Australian, and Canadian data in GHCN-Daily are updated monthly, but for other countries the delays in the latest daily data can be substantial. Most of the new results presented below will be based upon GHCN-Daily directly or indirectly. Under indirect use we mean the use of updated national data sets (e.g., for Russia and Mexico) that are currently in preparation for open access through GHCN-Daily but have already been used in our analyses. Results of analyses of intense rainfall several national and regional analyses of changes in heavy and extreme precipitation will also be provided. At present, large-scale analyses of heavy (extreme) precipitation changes at the sub-daily (hourly) time scale are available only for the conterminous United States where a dense network of hourly precipitation (Hourly Precipitation data, HPD, Figure 5.1.9) has been operational for the past 100 years and these data (so far, since 1948) have been recently digitized. Changes (especially at extreme intensities) fortunately are mostly unaffected by the impact of numerous changes in precipitation instrumentation and observational practices. The most serious problem that causes biases in measured precipitation is wind-induced turbulence over the gauge orifice (Sevruk 1982; Goodison et al. 1998; Adam and Lettenmaier 2003) which for intense rainfall can be ignored starting with the rate of above 2 mm h^{-1} (Bogdanova 1966; Sevruk 1982). For intense snowfall, the impact of wind on the rain gauge catch can be substantial (Figure 5.1.10). Therefore, traditionally when studying the precipitation changes in the regions with a substantial fraction of frozen precipitation relative changes are assessed, i.e., changes expressed in percent of the long-term mean or in percent of standard deviation, changes in return periods, etc. (cf., Karl and Knight 1998; Stone et al. 2000; Førland and Hanssen-Bauer 2000; Kattsov and Walsh 2000; Zhai et al. 2005; Kunkel et al. 2009; Zhang et al. 2010).

Due to a greater ability of the warm atmosphere to hold moisture compared to the cold atmosphere, the highest values of precipitation over most of the globe are observed in liquid form and the focus on intense and extreme precipitation in this Chapter allows us to skip the still unresolved issues of accuracy of frozen precipitation measurements as well as systematic changes in their biases. Instead we describe two somewhat related problems in liquid precipitation measurements that can affect estimates of intense precipitation changes. The sensitivity of the rain gauges, i.e. their ability to report the lowest amounts of precipitation, can unexpectedly affect statistics of rainfall intensity. First, we present a few examples and then discuss their consequences.

In the late 1930s, the Norwegian Meteorological Service began sending letters of appreciation to its observers. In response, they began working even more diligently and reported each 0.1 mm of precipitation in their daily reports. Fifty years later, Groisman et al. (1999) found a significant century-long increasing trend in the number of wet days over this nation that was completely explained by a jump in the number of rainy days with … 0.1 mm that were practically absent in the past records.

In 1966-67, the Hydrometeorological Services of the former Soviet Union and later of Finland made concise efforts to account for light precipitation “to the last drop” and introduced wetting corrections to each non-zero precipitation measurement (0.2 mm for liquid and 0.1 mm for frozen precipitation; when at least one drop was extracted from the gauge it was assumed to be a 0.1 mm). The number of days with precipitation increased and the total reported precipitation increased by 5-10% and up to 30% in the Arctic regions (Shver 1976; Groisman and Rankova 2001).

After Canada switched from British units to SI (for precipitation, the measure changed to mm instead of 0.01 inch) all statistics of rainfall and snowfall occurrence became “slightly” incomparable. This and several changes in instrumentation (cf., Metcalfe et al. 1997; Mekis and Hogg 1999) made it very difficult to assess changes in the light precipitation occurrence over this nation (let us recall that even in Southern Canada the median daily precipitation total is on the order of 1 mm).

Figures 5.1.11 illustrates the inhomogeneity of information stored in the U.S. and Canadian digital archives regarding the low intensity precipitation. For example, in the U.S., the number of

0.01 inch precipitation reports steadily growth from 6 yr^{-1} to 13 yr^{-1}. Reports of 0.02 and 0.03 inch daily precipitation remained steady since the 1940s but prior to these years they were also reported less frequently. During the 1961-1990 period, on average, there were 88 days with non-zero precipitation nationwide and ~19 of them (22%) reported from 0.01 to 0.03 inches of precipitation. In the beginning of the 20th century, these numbers were close to 11 days and one hundred years later exceeded the 20 days threshold, i.e., nearly-doubled. In the northern U.S. along the Canadian border the effect is even more pronounced. During the 1961-90 period, on average, there were 118 days with non-zero precipitation and ~30 of them (25%) reported from 0.01 to 0.03 inches of precipitation. Since the beginning of the 20th century, the number of reported 0.01-inchers nearly doubled and the number of reported 0.02- and 0.03-inchers increased from ~8 to ~12 in the 1940s and remains steady thereafter.

We actually expected this problem only on the Canadian side of the border (cf., Vincent and Mekis 2006). These authors reported very large trends in number of days with precipitation across the entire Canada treating them as a true finding. We hypothesized that this is a result of changing of instrumentation and observing practices in Canada (Groisman et al. 2003). Figure 5.1.11 (top panel) supports this, our claim, and illustrates the inhomogeneity of information stored in the Canadian digital archives for the southernmost part of the country along the US border. Here, the number of daily precipitation reports of less than 0.5 mm changed jump-wise from 2 yr^{-1} to 14 yr^{-1} after introduction of metric (instead of British) units and introduction of rain gauges with a transparent bucket. The number of reports of daily precipitation in the interval within 0.5 – 1.0 mm interval in this part of Canada has also changed during the past 100 years by 90% from ~ 10 yr^{-1} to ~19 yr^{-1}.

After encountering the problem with low intensity precipitation reporting, it is worthwhile to sacrifice the low precipitation daily bins (in any case they were not reported consistently during the past century) and to find the thresholds (cutoff breakpoints) after which we can reliably analyze time series of "days with sizable precipitation" (i.e., days with precipitation above these thresholds) as well as precipitation totals over southern Canada. Various cutoff breakpoints were used to eliminate a range of smaller values from the analyses of "days with precipitation". Below, we show an empirical approach to assure that there is a possibility to assess the "sizeable" precipitation trends even in the presence of the inhomogeneities reported in Figure 5.1.11.

We discarded the day with precipitation below 0.01" (using cutoff value 0.31 mm), and compared the trends across the border. Then we incremented the cutoff value by another 0.01", etc. up to days with precipitation below 0.1" (or 2.6 mm) from both sides of the border and compared trends for the past century. We did not see problems with the U.S. trends (very soon they became invariant to the breakpoint selection). But, for southern Canada, in order to extract what appear to be reasonable trends (i.e., similar to those observed in a close southward proximity), it was found that only the value 2.31 mm (which eliminates 0.09" and lower daily precipitation events) is a safe value along the entire border (Figure 5.1.11, middle panels). Further testing indicates that it is possible to use smaller cutoff points for days with precipitation, if we are intending to analyze the data only after 1978-1980 (the years when most of changes causing homogeneity problems last occurred in the Canadian observation practice). Similar analyses performed for total precipitation and for days with heavy (upper 10%-ile) and very heavy (upper 1%-ile, not shown) precipitation show that the "breakpoint" problem is not acute and does not create changes between the slopes of trends across the U.S.-Canadian border (Figure 5.1.11, bottom panels).

Any analysis of temporal changes in the HPD data has to account for one important change at the network since 1960s: From 1948 to 1960 all of the gauges recorded with a resolution of 0.254 mm (0.01 in.). These gauges were gradually replaced so that currently more than 85% of HPD gauges record to a resolution of 2.54 mm. Fortunately, this gradual replacement of gauges is well documented and it is possible to homogenize the time series (cf., Groisman et al. 2012) for the entire period of record. This conversion is of critical importance. Without this adjustment for gauge resolution, an unaware user could generate grossly false conclusions about the changes in precipitation duration and intensity. The accuracy of the COOP network rain gauges has remained 0.254 mm throughout the entire period of observations.

All the above have one problem in common: instability of reporting of light precipitation (in the daily and hourly totals). The researchers who intend to assess the upper tail of the precipitation distribution using upper percentiles, can be hurt from the low end of this distribution because

- estimates of the number of observed no-rain days and estimates of "daily intensity" (precipitation totals divided by the number of days with precipitation) can be contaminated by artificial trends;
- on the hourly time scale, estimates of the rainfall duration and intensity trends can be extraordinarily high (and opposite in sign) if the resolution of the gauges changes with time;
- the attempts to estimate the daily precipitation distribution (e.g., with gamma-distribution) and its changes with time can be affected by the changing numbers of low values that are close to zero (which over most of extratropics are the most frequent precipitation events); the following assessment of the upper tail of this distribution and its changes will be in trouble; and finally,
- the upper percentiles of daily precipitation each year can be based upon a very different fraction of rain days (cf., Figure 5.1.11).

Different ways to handle this problem can be found in (Groisman et al. 1999, 2012; Rosenberg et al. 2010; and Mishra et al. 2012).

The last (less frequent) data problem that may affect researchers who study heavy precipitation is a changing amount of the accumulated daily precipitation totals with time. So far, we found only one country (Australia, cf., Groisman et al. 1999) where this problem is sufficiently severe and had to be resolved prior to further analyses of heavy precipitation changes[7].

Geographical distribution of changes in intense precipitation

Approximately 15 years ago, studies of global-wide changes of intense precipitation were virtually absent because the appropriate data sets did not exist (i.e., long-term time series with daily and/or hourly resolution from dense international networks of meteorological stations). National data sets existed but they were not shared simply because there appeared to be little interest in working with them. The situation gradually changed after the first reports about potentially dangerous tendencies of increasing of intense rainfall in the upper percentiles of its daily distribution (Iwashima and Yamatomo 1993; Karl and Knight 1998) and theoretical expectations of further development of these tendencies in the warmer climate projected with human-induced changes in the atmospheric composition (Section **5.1.2**).

[7] When the post-offices in this country switched from the 6-days a week to 5-days a week work schedule, a substantial part of the national precipitation network located at these offices began reporting Monday extreme rainfall and the previous days were … missing.

Initially, the number of stations used in these analyses was quite modest. For example, the first daily station data set employed by Karl and Knight (1998) included the long-term daily precipitation time series of only 182 stations over the contiguous U.S. (compared to more than 6,000 stations used in the present national analyses such as USCCSP 2009). This paucity of stations in turn allowed analyses of intense precipitation only above the upper 5^{th} percentile or annual/monthly maximum rainfall that (a) did not qualify to be truly extreme events and (b) in the case of annual maximum can be misleading in the regions where precipitation changed at both ends of its distribution (cf., Box Insert in Section **5.1.1**). It became clear that without preparation of expansive international precipitation data sets with daily time resolution, no further advance would be possible. First efforts to compile such data set were made at the U.S. National Center for Atmospheric Research (Spangler and Jenne, 1984; Liebmann et al. 1999, 2001) and the NOAA National Climatic Data Center (cf., http://www.ncdc.noaa.gov/oa/gsod.html; http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/). These efforts were supported by the World Meteorological Organization (WMO) with organizing regional workshops devoted to analyses of regional daily data. Totally during the 1998-2008 period, sixteen such workshops were organized (Peterson and Manton 2008) and their results were later reworked into scientific papers (cf., Peterson et al. 2002; Easterling et al 2003; Aguilar et al. 2005, 2009; Sensoy et al. 2007; etc.). Furthermore, NCDC invited scientists from different countries who have expertise (and access to scientific quality national data sets) to visit the Center for joint data quality analyses (e.g., Groisman and Rankova 2001; Ren et al. 2005) and joint assessments of changes in heavy precipitation (Groisman et al. 1999; Easterling et al. 2000; Groisman et al. 2005; Alexander et al. 2006). Gradually from these studies, a mosaic of systematic changes in intense precipitation over the globe was compiled and revealed several systematic features of changes in intense and heavy precipitation (Figure 5.1.12):

Over most of the extratropics in the rainy season with the highest rainfall, intense precipitation (rain events in the highest upper percentiles of daily distribution) became more frequent during the past 50-60 years.

In the tropical zone the sign of changes vary; there are regions where heavy precipitation frequencies increased and the regions where they decreased.

If there was a significant increase in mean seasonal precipitation, the increase in the upper percentiles (heavy precipitation) was disproportionally large compared to changes in mean precipitation.

In several large regions (e.g., Northern Asia, Mediterranean, central Mexico) where the mean precipitation did not change or even decreased, the heavy precipitation events nevertheless became more frequent.

Figure 5.1.12 is a third generation of the picture first presented in Easterling et al. (2000) and thereafter in Groisman et al. (2005) where signs (+ and -) show the regions with observed changes in heavy precipitation that follow the pattern outlined above: changes in mean precipitation are less or insignificant while changes in heavy/very heavy precipitation are statistically significant. Initially, the shading on the map indicated the countries for which the authors' team had and analyzed the data themselves but gradually the distinction became only historical because other scientists have studied most of these regions as well and reached similar conclusions. While there were efforts to unify the definitions used to characterize intense (heavy, extreme) precipitation over the globe (cf., Frich et al. 2002), they cannot be considered successful. Different research agendas faced by the scientists in different countries and different disciplines (civil engineers, hydrologists, climatologists, and agriculturists) and different amounts of data they had to address these agendas actually dictated the selection of thresholds used for definitions of terminology of intense precipitation categories (cf., discussion in Section **5.1.1**). Therefore, the regional results that we shall describe below are diverse and thus require individual description.

Moreover according to our classification in Table 5.1.1, most of these results are devoted to changes in the frequency of heavy and very heavy precipitation events but not of extreme events (although the authors frequently name them "extremes", e.g., the upper 5% of daily rainfall distribution or the annual maximum rainfall). We again have to warn about the use of "dynamic" definitions when for each year the high end of daily rainfall distribution is selected to characterize very heavy and/or extreme rain events. In dry years these events may be "not at all heavy or extreme", and in some regions may hide the actual changes at the high end of the daily rainfall distribution [cf., Box Insert in **5.1.1**].

Below, we decipher signs presented in Figure 5.1.12 as they were first presented in Groisman et al. (2005) updating and/or supporting them with results of other studies.

In European part of the former USSR, more than 700 long-term stations during the period 1936-1997 were available to Groisman et al. (2005) for analyses of "heavy", "very heavy", and extreme precipitation defined as upper 5% to 10% (heavy) 1% to 0.3% (very heavy) and 0.1% (extreme) respectively. Most of newly independent states of this territory (except Russia and Belarus) do not share sufficient volume of their meteorological observations with international archives. Therefore, now for similar analysis during the period 1936-2010 **in European part of the Russian Federation,** we can use the data of 335 long-term Russian stations. 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 approximately 95% of the daily precipitation events are still less than 10 mm day^{-1}. Table 5.1.2 summarizes the results of trend analyses for these two regions for the summer season. Both show a large increase of about 10% in summer precipitation in the region for the study period although the century-long increase is smaller (e.g., Groisman and Rankova 1991). During the same period, the rate of increase in heavy precipitation, in very heavy precipitation, and in extreme rainfall[8] was higher than for mean summer 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 *annual* precipitation are also statistically significant at the 0.05 level or above for the former USSR during the period 1936-1997. For the extended period 1936-2010, the sign and absolute values of trends in very heavy and extreme *summer* precipitation became statistically insignificant. Updated precipitation time series for this region show a continuation of the precipitation increase as well as the increase of the frequency of intense rain events of various strength up to 2009. The rates of change did not change appreciably compared to the annual events for the shorter period but the thresholds and the level of interannual variability of the area-averaged number of days with heavy and extreme summer rainfall are higher than those for precipitation during the entire year. Moreover in 2010, a dramatic summer drought (cf., Mescherskaya et al. 2011; Barriopedro et al. 2011) contributed to this variability. It did not reverse the trends in the frequency of heavy, very heavy and extreme rain events in this part of the world but zero values as the last points of time series of very heavy and extreme rain event counts did not add to trend estimates either.

[8] For the summer season, we use here a 0.3 percentile as a threshold to define extreme rain events that occur in these two regions approximately once per 10 years.

Fennoscandia is very well covered by precipitation stations (Figure 5.1.9), 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 2005). There were previous reports describing the total precipitation increase in Northern Europe (Hanssen-Bauer et al. 1997; Heino et al. 1999; Førland and Hanssen-Bauer, 2000; Folland and Karl 2001), but they all reported a smaller relative change compared to Groisman et al. (2005) for changes in "very heavy" precipitation frequency defined as the upper 0.3% of daily precipitation events both in summer (a season with the most intense precipitation) and throughout the year (Figure 5.1.13). All increases have occurred since 1980s. The average regional upper 0.3% thresholds are 50 and 45 mm for summer and annual respectively.

A 66% increase to the early 2010s of the summer frequency of very heavy daily rain events (a region-wide average of 50 mm but along the Norwegian Sea Coast much higher) which in the early 1950s occurred approximately once per decade became a large problem because it coincided with changes in an intra-season distribution of the rainy days. Recently for Norway, Zolina et al. (2012) after analysis of the daily data of more than 200 national stations, showed a simultaneous shortening of wet periods for the past 60 years in southern Norway along the Sea Coast in the warm season, and their significant increase in the cold season. This implies that while the winter precipitation can be more equally spread within the larger wet spells, in summer, intensity of daily rainfall should disproportionally rise (as predicted by Groisman et al.1999) and is shown in Figure 5.1.13. It is worthwhile to note that the summer precipitation totals area-averaged over Fennoscandia did not change during the past 60 years[9].

Canada. Stone et al. (2000) while analyzing heavy precipitation over Canada had to account for restrictions imposed by frequent low intensity precipitation over most of the nation with respect to the definition of heavy precipitation. They argue that when the upper decile of daily precipitation events can correspond to a threshold of ~0.5 mm, it is difficult to consider these events "heavy" (e.g., in Northern Canada). Furthermore, our analysis (cf., Figure 5.1.18) shows that the analysis of frequent light precipitation events in Canada is challenging but when looking for precipitation above 5 mm d^{-1} the process is trouble-free across the entire Canada. Fortunately, Stone et al. (2000) in their definition of heavy precipitation used this value as a minimum threshold (T_5 = 5 mm d^{-1} (1+n), where n =0,1, 2, etc.; the n-values were selected at each station individually in order to secure at least 5 events per year in each 3-month-long season of the 1960-1990 reference period). Such sophisticated selection allowed them to analyze the changes of sizeable precipitation events at the upper end of the daily distribution across the entire nation that (a) are all above 5 mm and (b) consider on average approximately 20 precipitation events per year as heavy events. The authors grouped their stations in 5 large regions with similar patterns of precipitation changes (southeast, northeast, Arctic Canada, southwest, and northwest). The frequency of thus defined heavy precipitation events during the analyzed period of 1950-1995 increased over the densest populated part of Canada, the *southeast*, in spring-summer season (April through August). This region is relatively humid (thus the selected n-values there were among the highest in the nation). Over *northeastern Canada* they reported an increase in heavy precipitation in the spring months and in the last five months of the year. Over

[9] During the past 60 years, annual totals of *measured* precipitation over Fennoscandia have increased with a mean rate of 30 mm per decade. Part of these increase is real but a sizeable fraction of increase is due to (a) a better snowfall catch of the new Finnish gauges (Figure 5.1. 10) and (b) a general shift in the ratio between liquid and frozen forms of precipitation with regional warming (all contemporary rain gauges catch a larger fraction of rainfall than of snowfall; cf., Førland and Hanssen-Bauer 2000; Goodison et al. 1998).

Arctic Canada, heavy events frequency increased significantly during most of the year (except the summer months). Over *northwestern Canada*, heavy precipitation events increased in winter and spring, while no changes in heavy precipitation were documented in *southwestern Canada* in any 3-month-long part of the annual cycle. It is worthwhile to note that nowhere across the nation was there found a large region and a three-month-interval where statistically significant decreases in heavy precipitation were documented during the 1950-1995 period (Stone et al. 2000).

Pacific coast of Northwestern North America is the only large high latitude region with both large annual precipitation totals and a sufficiently dense precipitation network available for our analyses in the Western Hemisphere. The mountainous character of these two regions makes the heavy precipitation here an important issue because of the landslide and flash flood danger. Figure 5.1.14 shows the time series of the frequency of heavy and very heavy precipitation in southern Alaska (south of 62°N) and British Columbia, Canada (BC; south of 55°N). These time series were first presented by Groisman et al. (2005) and here they are updated to 2010. In both regions, precipitation increased during the period of record, but the double-digit increases in the frequency of heavy and very heavy precipitation are especially noteworthy (Table 5.1.3). Given the high thresholds for these events, these changes reflect an increasing societal and/or environmental threat in both areas. Note that in southern Alaska in the last eight years the frequency of very heavy precipitation returned to long-term mean values and the trend of their occurrence is statistically insignificant.

Mexico. Analyzing variability of the heavy daily precipitation occurrence (upper 10% and 5% of daily rain events mostly in the winter season) in the northern Baja California during the 1950-2000 period, Cavazos and Rivas (2004) linked this occurrence to the strong impact of El Niño events and neutral ENSO conditions in the region. While linking most of the variability to ENSO and tropical moisture transport into the region associated with El Niño “pineapple express”, they also document a shift of heavy precipitation distribution, with a relatively dry period and less variability during 1950–1976, followed by a relatively wet period and more variability during 1976–2000. Variability in this dry region means more frequent heavy rain events some of which caused flooding and losses of life in the city of Tijuana. Southward, over the central Mexican Plateau, the changes in summer heavy precipitation (the upper 5% of daily rain events or those above the 25 – 35 mm thresholds) followed the change of the mean precipitation that was decreasing in the last three decades prior to year 2005 (Groisman et al. 2005). 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) has 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.

Contiguous United States (CONUS). Studies of the changes in heavy and very heavy precipitation over CONUS (cf., Karl and Knight 1998; Groisman et al. 2001, 2004, 2005; Kunkel et al. 1999, 2003, 2007) were summarized in USCCSP (2009). In this National Assessment it was shown that over the entire eastern two thirds of CONUS, daily and multi-day precipitation events became more frequent and the most prominent increases occurred over the northeastern quadrant of CONUS (Figure 5.1.15).

In the southeastern U.S. very heavy and extreme precipitation associated with tropical storms and hurricanes has increased (Knight and Davis 2009; Kunkel et al. 2010; Wang et al. 2010) while other intense rainfall occurred less frequently in the past decades (archive of Groisman et al. 2012). This development allowed Wang et al. (2010) to conclude that during the 1948-2007 period, the Southeast summer rainfall exhibited higher interannual variability with more intense summer droughts and anomalous wetness in the second 30 years (1978–2007) than in the prior 30 years (1948–77).

For the eastern regions of CONUS, the recent elevated numbers are the largest since reliable records begin (1895). For western regions, the recent decades are comparable to the early part of the historical record. In the southeastern U.S. very heavy and extreme precipitation associated with tropical storms and hurricanes has increased while other intense rainfall occurred less frequently in the past decades (Knight and Davis 2009; Kunkel et al. 2010; Figure 5.1.2, archive of Groisman et al.2012). For the past three decades, ***in the central United States***, Groisman et al. (2012) reported a considerable increase in very heavy and extreme rainfall (up to 40% increase for daily and multi-daily events above 155 mm or 6 inches; Figure 5.1.16). However, (after checking all other possible causes in addition to the ongoing global warming) they hypothesized that at least a part of this tremendous rise in extreme rainfall might be associated with local anthropogenic forcing, intensification of land use and doubling and/or quadrupling of corn and soybeans yield in the area (cf., Sub-section **5.1.2c**).

In addition to the frequency changes of intense precipitation, its intensity has increased over the entire CONUS. Figure 5.1.17 (top) shows nationwide changes in intense precipitation that comes in fixed 1-day-long and 2-day-long strings of consecutive rain days (defined here as a day with daily total above 12.7 mm or 0.5 inch). Together, 1-day- and 2-day-long strings represent 97.5% of all intense rainfall days and deliver 93% of its precipitation. Over the Midwest, the rainfall that comes in 3-day- and 4-day-long consecutive days has also increased significantly (Figure 5.1.17, bottom). In this part of the United States, frequency of the four-day-long consecutive rainfall events (that comprise *on average* 5 inches of rain) has been increasing in the past decades.

Povl Frich (1999) developed a suite of indices that were proposed to use as characteristics of climatic change. The pioneering idea beyond this proposal was a comprehensive suite of daily characteristics of temperature and precipitation that (together with the mean characteristics of climate) includes characteristics that can be used to describe anomalously high (low) climate conditions (extremes) and their changes. Among these characteristics were variables that are well suited to describe changes in intense precipitation. These characteristics do not describe "extreme" rainfall as a very rare event (cf., as defined in Table 5.1.1) but instead these precipitation indices are flexible, easy to calculate, and their suite (with some reasonable modifications) can be used to describe heavy and very heavy precipitation across the world. These indices include the number of days with precipitation above 10 and 20 mm, annual daily maximum rainfall, maximum annual 5-day rainfall total, upper 95% and 99% percentile rainfall totals and counts of daily events. These indices have been broadly used in regional and international assessments of intense precipitation change (cf., Frich et al. 2002; Alexander et al. 2006; You et al. 2008; Caesar et al. 2011; Easterling et al. 2003; Peterson et al. 2002; Aguillar et al. 2005, 2009; etc.). Below, we shall name them Frich indices. Frich indices were used in near-global and continental assessments of changes in the climate "extremes" (cf., Frich et al. 2002; Klein Tank and Können 2003; Easterling et al. 2003; Moberg et al. 2006; Haylock et al. 2006; Alexander et al. 2006). The most comprehensive among these near-global assessments (Alexander et al. 2006; cf. Figure 5.1.9c) is described below.

For the 1951-2003 period, Alexander et al. (2006) reported near-global increase in the number of days with precipitation above 10 mm and in the contribution of the upper 5% of rain events to the annual totals. The pattern of the regions with increases in intense annual precipitation includes most of North America, regions surrounding (and including) the La Plata River Basin and Southern Brazil, most of Europe, and large areas in southern and eastern Asia. Analysis of the seasonal changes in the maximum 5-day precipitation totals (RX5day) shows a quite similar pattern as two other annual indices except summer (JJA) when the areas with decrease in RX5day became more spacious and include (for example) Western Europe, extratropical Far East, most of Australia, and Southern Africa.

For the 1901-2003 period, Alexander et al. (2006) repeated their trend analyses over a smaller part of the land (CONUS, southern Canada, Europe, Russia, and Australia) and found at the long-term stations in these regions an overwhelming tendency of increase in annual characteristics of intense precipitation. This coherent signal over most of the extratropics (if true) is spectacular but it also raises some concerns (cf., Figures 5.1.10-5.1.11) because (a) national practices in all these countries "improved" their precipitation networks many times during the past century in order to provide better measurements (which means more rain is reported by gauges); (b) the redistribution between frozen and liquid precipitation has been shifted with global warming which also resulted in a better gauge catch (cf., Førland and Hanssen-Bauer 2000); and (c) in Australia, the number of rainfall totals accumulated during the weekend significantly increased after the national Post Office, where many rain gauges reside, ended its Saturday service (Groisman et al. 1999). It should be determined if and how these instrumental inhomogeneities affected statistics of intense rainfall in the data sets used by Alexander et al. (2006). Common wisdom hints that (except for the Australian "Post Office" factor and the regions with cold season maximum precipitation) the impact of instrumental inhomogeneities on changes of annual daily maximum rainfall should be miniscule.

Figure 5.1.12 generalizes the results for the regions that were not initially covered in Groisman et al. (2005) as well as provides updates and new findings for the regions that were initially assessed in that work. Table 5.1.4 provides a summary of these findings (except those that have already been described above). In these studies, time intervals assessed are different and different characteristics of heavy precipitation were considered, but everywhere these were the estimates of changes in heavy and (in some cases) very heavy precipitation according to definitions of Table 5.1.1. Data analyses that focus on extreme rain events and their changes in the contiguous U.S. are further presented in the next Sub-section.

Changes in extreme precipitation over the contiguous United States

Practically all results presented in the previous two sub-sections of 5.1.3 describe regional changes in heavy and very heavy precipitation events (according to classification presented in Table 5.1.1). Changes in extreme precipitation are considered in fewer studies and are concentrated in the areas with dense networks of long-term precipitation time series. Contiguous United States is one of such regions. Three different types of analyses were conducted here to catch the changes in extreme precipitation. Each type is presented in a number of publications and research reports and below we assess a few of them that are representative of these analyses.

Efforts to update NOAA Atlas No. 2 that contains precipitation frequencies of different intensity and duration have been conducted during the past 10 years (new NOAA Atlas 14; Bonnin et al. 2004-2012). The approach of this study is as follows: All precipitation events at each NOAA meteorological station in the U.S. (there more than 25,000 such stations and thus the work is very arduous) are documented, their duration, total, and mean intensity (e.g., hourly, 6-hourly, daily, 2, 7, ... 45 days totals, etc.) are defined and their frequencies are estimated during the period of record and separately for the past three decades to check the differences with the previous NOAA Atlas (No. 2). Among the most important practical tasks of the Atlas creators were calculations of exceedance values of rainfall for different return periods (1, 5, 10, 25, 50, 100, up to 1000 years). For large return periods for most of the stations (for return periods of 100 years and above, for all), these calculations cannot be done without some assumptions. Generally, there were two of them: (a) it was assumed that extreme value distributions, Gumbel 1954; Generalized Extreme Value, GEV (Coles 2001); and Pareto (Hardy 2010) can be employed to approximate the upper tails of precipitation distribution of different duration (accumulated totals); and (b) that some regional features (shape) of the upper tail precipitation distribution are similar (regions were selected using L-moments method, cf., Hosking 1990, Hosking and Wallis 2005). After comparison of the exeedance dynamics for 2 and 5 years return period (i.e., for very heavy precipitation events), Bonnin et al. (2011) concluded that their results broadly coincide with findings of Groisman et al. 2004, 2005): trends in exceedances at one-day and multiday durations were statistically significant and increasing for the Ohio River Basin and surrounding states. They also found that for the Semiarid Southwest there are no significant trends in extreme precipitation during the post-World War II period. For larger return periods (25 years and above) the authors concluded that their data-driven approach cannot deliver statistically significant trend estimates (confidence intervals of these estimates were ±30% while the absolute values of trends were on the order of magnitude less).

Figures 5.1.3 and 5.1.16 have already shown results delivered by a direct approach used by Groisman et al. (2012) in order to investigate intense precipitation (including extreme rain events) over southeastern and central regions of CONUS. They deliberately simplify the area-averaging by analyzing the multi-decadal total frequencies at all stations available at that period omitting to account for possible clusters (in any case the assessment based upon fixed thresholds does not allow for accurate regional representation of extreme precipitation events frequency) and carefully accounting only for the average number of stations available during these periods in order to receive the accurate “per station” estimates. The last liberty was also justified by the period used for analyses (1948-2009) that was initially rich with data from well-developed gauge networks. Figure 5.1.18 shows similar estimates but for the northwestern (Washington, Oregon, and Idaho) and southwestern (Four Corners; Utah, Colorado, Arizona, and New Mexico) States.

Climatology of intense precipitation distribution for these mostly dry regions is very different from that for the eastern U.S. (cf., Table 5.1.1) and is therefore shown separately in Table 5.1.5. Table 5.1.5 shows that 79% of all intense precipitation events in the northwestern U.S. are delivered by days with moderately-heavy precipitation (over entire CONUS this mean number is close to 50%). Days with precipitation in the range from 1 to 3 inches comprise another 20%(defined for the eastern two thirds as heavy rain events but here the significant fraction of these events (those in the range from 2 to 3 inches) can be easily quantified as very heavy according to the “percentile” scale presented in Table 5.1.1). Only one percent of intense rainfall is classified into the greater than 3 inch daily rainfall category. Frequencies of only these rain events have increased during the past three decades compared to the previous three decades (Figure 5.1.18). The probabilities of rare daily rain events (shown in Table 5.1.5), and the inverse values that are customarily interpreted as approximations of return periods (e.g., for events above 5 inches this return period estimate looks like 100 years), should be interpreted with caution due to large spatial heterogeneity of precipitation pattern across the Northwest. Our estimates are averaged over 320 long-term stations of three states. Therefore, stations along the Pacific Coast and windward slopes of Cascades and Olympic Ranges reported most of regional extreme precipitation events, while the stations eastward of the coastal mountain ranges did not deliver many extreme rainfall events and participating in regional averaging reduced the probabilities of event occurrence shown in Table 5.1.5. When we selected the eastern boundary of the "northwesternmost" U.S. by 121.5°W (i.e., separating 126 stations in the wet coastal regions of the Oregon and Washington States), our counts of the very heavy and extreme daily precipitation events of four inches and above practically did not change, but their frequencies per year per station in the region increased to 0.091, 0.029, and 0.020 for events between 4 and 5, 5 and 6, and above 6 inches respectively. Analysis of the results presented in Table 5.1.5 and Figure 5.1.18 provides an explanation of the peculiarity of the northwestern U.S. revealed in Figure 5.1.3. Only in the Northwest, this Figure showed a relative increase in the fraction of moderately-heavy precipitation events compared to other intense rain events (above 25.4 mm). In fact, the frequency of the moderately heavy precipitation events (79% of all days with intense precipitation) did not change. The number of days with precipitation in the range from 1 to 3 inches decreased (another 20% of all days with intense precipitation) and this decrease predefined the sign of changes in the fraction of moderately-heavy precipitation events within the intense rain events distribution. Changes in the upper 1 percent of intense rain events distribution were in a "right direction" (increase, as in other regions of the eastern and central U.S.). However, their increase was insufficient to overweight a decrease of the less intense but 20 times more numerous rain events (cf., Table 5.1.5 and Figure 5.1.18).

Southwestern U.S. (Four Corner States) is a dry region compared to all other parts of CONUS. As a result, the scale of intense precipitation is shifted to lower ranges and on average the rain days with totals in the range of 12.7 mm to 25.4 mm occur here 6 times per year and comprise 86% of all days with intense precipitation. Another 12.5% of rain events come in the range from 1 to 2 inch day^{-1} and these events occur less than one per year (Table 5.1.5). Frequency of these events as well as the frequency of the two following ranges has increased in the past three decades compared to the previous period (Figure 5.1.18) while the frequency of rain days with daily totals above 4 inches decreased. It should be noted that whatever the spatial inhomogeneity across the region is (e.g., mountains against the lowlands and the low elevation biases of the GHCN-Daily sites used in our analysis), the total number of catastrophic rain events reported by 487 long-term stations in this region during the past 62 years was 97, 23, and 11 for 4 inchers, 5-inchers, and for rain events above 6 inch day^{-1} respectively. These events (according to Figure 5.1.18) had occurred more frequently in the first three decades after World War II than thereafter.

DeGaetano (2009) analyzed the 30 maximum daily accumulation precipitation totals at the 1061 long-term high quality stations of the U.S. Historical Climatology network during the 1950-2007 period. The analysis was conducted 4 times using 30-yr running intervals, lengthening periods (30, 40, etc.) and for the starting dates of 1950 and 1960. At each site and for each period, he estimated the parameters of the GEV distribution[10] that fit these maximums and assessed the changes in these parameters with time over CONUS. Such analysis allows estimating the pattern of the return period precipitation amounts and their trends. His analysis revealed the regions where the changes in the GEV location parameter are significant (increase) and that (a) other GEV parameters did not change systematically with time and (b) there are regions (California, Intramontane regions, and Southeast) where no changes in extreme precipitation distribution were revealed. Areas where a significant increase in the return precipitation amounts was

[10] The routine suggested by Kharin and Zwiers (2005) was used to estimate the location, shape, and scale parameters of the generalized extreme-value (GEV) distribution.

observed coincide with the areas shown in Figure 5.1.15 (the northeastern quadrant of CONUS) with an addition of the Pacific Northwest (coastal areas). After analysis with sub-division of the Northwest into wet humid and dry parts with appropriate recalculation of the event frequencies (Table 5.1.5) this increase is also supported by estimates shown in Figure 5.1.18. It is important to note that the estimates provided by DeGaetano (2009) (precipitation amounts for 2, 30, and 100 year return intervals) directly address the concern of the civil engineering community. Their general support by the independent estimates that do not rely upon any assumptions about the distribution of extreme precipitation strengthen the conclusions of this study and increases its practical importance.

Kunkel et al. (2012b) presented several metrics used to estimate extreme precipitation changes over CONUS including one based upon time varying peaks over specified thresholds using statistical extreme value analysis (Tomassini and Jacob 2009; Cooley and Sain 2010). For each year, the station-specific thresholds were set to the 97th percentile over days with at least 1 mm of rainfall (i.e., on average for CONUS, at one to three rain events per year). Next, the exceedances of these thresholds were approximated with a dynamically changed generalized Pareto distribution, and possible changes during the 1948-2010 period in one of its parameters responsible for increase/decrease in 20-yr return period values were tested at each long-term GHCN-daily station. This statistical analysis shows that about 76% of all CONUS stations experience increases in extreme precipitation, with 15% showing a statistically significant ($P < 0.05$) increase based on station-specific two-sided tests. A field significance test based on resampling entire years of data (to preserve spatial structure and within year seasonal patterns) was statistically significant ($P < 0.001$). Across the eastern two-thirds of CONUS these exhibit a high degree of spatial coherence. Regions with greater numbers of stations with decreases are of smaller spatial extent and include the coastal Northwest (cf., Figure 5.1.18 for heavy precipitation). Moreover, when mapped, the results of this analysis indicate that everywhere across CONUS extreme precipitation (20 yr return period values) has increased during the past 62 years; however not all of these changes can be claimed to be statistically significant. In particular, this type of analyses claims that over Southern California and the Four Corners States the extreme precipitation has increased, while direct assessments of changes in extreme precipitation for California (Bonnin et al. 2011) and the Four Corners States (Figure 5.1.18) do not confirm this claim.

The above brief intercomparison of parameterized (distribution-based) and direct approaches shows that in the regions where a linearity of changes in heavy, very heavy, and extreme precipitation has occurred (the signs of changes are the same and only the rates of changes can be different), all approaches give non-contradictory similar results. However, when extreme distribution parameter estimates (fitting the distribution curves) are observed in the regions where non-linear changes in intense precipitation have occurred (Northwest, Southwest, Mountains), the results based upon this fitting (specifically our conclusions about changes in extreme precipitation based upon this fitting and follow up extrapolations) may be compromised. For example,

- in the regions along the Pacific Northwest coast, extreme rainfall has increased but analyses based on heavy rainfall in this region will generate opposite conclusions (cf., Figure 5.1.18, left panel and DeGaetano 2009 versus Kunkel et al. 2012b);
- extreme rainfall in the Four Corners States became much less frequent in the past three decades (Figure 5.1.18, right panel) but analyses based on heavy and very heavy rainfall in this region again generate opposite conclusions (Kunkel et al. 2012b).

Finally, in the regions where different genera of extreme rainfall may occur (cf., Southeastern U.S.) their tendencies may well be different (Kunkel et al. 2012a) and even have an opposite sign (cf., Southeastern U.S., Figure 5.1.2).

Results based on daily data versus hourly data

Precipitation is not a contiguous process and even in the days with extreme precipitation above 155 mm over CONUS on average there are nine hours without rainfall (Figure 5.1.19). Therefore, assessments that use the daily time scale (daily totals) still can be considered incomplete answers to the questions about the precipitation dynamics especially during the warm season when rainfall immediately and in a multi-faceted manner contributes to the surface water budget. As Figure 5.1.19 shows for Northern Eurasia, short-duration rainfall is most frequent in summer when its significant fraction comes in convective rainfall form (Sun et al. 2001). Unavailability of large long-term data sets with sub-daily time resolution has so far prevented global analyses of how the global change would manifest itself across the smaller timescales, specifically, at the hourly time scale during the warm season (i.e., for rainfall). The importance of this time scale is difficult to estimate because there is a large difference in impact on environment and/or the human-built infrastructure if, for example a 25 mm d^{-1} rainfall total in fact occurred in an hour or less. The consequences for soil erosion (US SWCS 2003), flash flooding (Brooks and Stensrud 2000; especially in urbanized areas), and infrastructure damage (cf., Changnon and Westott 2002; Villarini et al. 2009) could be very different.

Changes in precipitation extremes under greenhouse warming are commonly assumed to be constrained by changes in the amounts of precipitable water in the atmosphere (Allen and Ingram 2002; Trenberth et al. 2003; Trenberth 2011; IPCC 2007). Global climate models generally predict only marginal changes in relative humidity (Bony et al. 2006; Min et al. 2011), implying that the actual amount of atmospheric precipitable water is scaled with the water vapor content of saturation, which is governed by the Clausius–Clapeyron relation. The common believe is that the mean precipitation change is not obeying this relationship, and the changes may be less than predicted (cf., Trenberth 2011). Indeed, changes in heavy ("extreme" in the language used by the modelers) daily precipitation in global climate models seem to be consistent with the 7% increase per degree of warming given by the Clausius–Clapeyron relation (IPCC 2007; Pall et al. 2007). In the absence of global analyses, below we present the recent findings accumulated in West Europe and the contiguous U.S.[11]

Using the 99 years of hourly precipitation time series at de Bilt, the Netherlands, Lenderink and van Meijgaard (2008) tested how the mean daily and maximum hourly rainfall intensity are changing with the surface air temperature variations. They concluded that when daily mean temperature exceeded 12 °C, hourly precipitation extremes increased with an increase in temperature twice as fast as expected from the Clausius–Clapeyron relation. Furthermore, analyzing the regional climate model output for central Europe, they found that this increase with summer surface air temperature in 1 h precipitation extremes typically exceeds $10\%K^{-1}$, and in a large area even $15\%K^{-1}$, while daily extremes increase typically by 5–10% per degree (i.e., in line with the Clausius–Clapeyron relation).

In the previous sub-section we describe analyses of extreme precipitation changes over CONUS with time conducted by Groisman et al. (2012). Here we describe a byproduct of this study

[11] In the former USSR (and currently in the Russian Federation, the dense network of the recording rain gauges exists, was used for climatological studies (e.g., Lebedev 1964) but has never used for climate change studies.

when the same comparison between the last three decades and the previous three decades (and numerous other possible partitions in two equal groups of years) was conducted to assess the possible changes in the internal precipitation structure such as mean and maximum hourly precipitation rates and precipitation duration (in hours). It was found that the climatology of these characteristics is systematically changing with increase of the rainfall range (cf., Figure 5.1.19). However, within each preselected range of daily or event totals, Groisman et al. (2012) found that mean and maximum hourly intensity and duration of precipitation daily and multi-day events do not noticeably change. This conclusion remained valid with all partitions (by time, by season, or by any other external factor that we employed) and for each of nine large regions of CONUS shown in Figure 5.1.19b. In Figure 5.1.20 we present one of these comparisons made several years ago (thus no data after 2007 were used) for the eastern half of CONUS east of the Mississippi River.

Results shown in Figures 5.1.16 and 5.1.20 hint that while very heavy and extreme rain days and events became more frequent with time; the processes that control the internal structure of these events, e.g., peak hour rain intensity and its duration do not change. Eventually, in the regions with increasing frequency of extreme rainfall, the frequency of higher peak rain intensity will be observed but this will occur “orderly” following the appropriate changes in daily rainfall intensities. The above conclusion is based upon the various analyses for diverse regions and seasons but only for the conterminous U.S. Thus, it well can be that in the tropics or in the polar regions, it will not be valid or, at least, the future users of these results need a leap of faith to assume such development without testing it.

Prolonged no-rain periods.

Karl and Knight (1998) and subsequent studies (Easterling et al. al. 2000; Stone et al. 2000; Groisman et al. 2004, 2005) all show that most of the precipitation increase over the U.S., Mexico, and Canada occurs due to an increase in the frequency of intense precipitation while the frequency of days with average and light precipitation does not change or decreases. The tendencies, which emerged during the past 35-40 years with a disproportional increase in precipitation coming from intense rain events (Groisman et al. 2004, 2005), should lead to breaks in the parallel increase/decrease of both total precipitation and precipitation frequency. For the U.S. this break was first reported by Sun and Groisman (2004) and for the northeastern quadrant of the conterminous U.S. was *projected* by Semenov and Bengtsson (2002) and thereafter confirmed by Groisman et al. (2005). Specifically, for the northeastern quadrant of the United States, the last authors reported an increase (or no change) in precipitation totals but decrease in the number of days with precipitation. If continued, this decrease in precipitation frequency may lead to an increase in the frequency of another potentially dangerous type of extreme events: prolonged periods without precipitation (even when the mean seasonal rainfall totals increase). Groisman and Knight (2007, 2008) investigated whether this unfortunate development is already occurring in the warm season during the past several decades over North America south of 55ºN[12], for the same period when we begin observing changes in frequency of intense precipitation events (i.e., since circa 1970). The most detailed description of the approach they used and results is provided in Groisman and Knight (2008) for conterminous United States.

[12] North of this latitude the station network density is generally insufficient for analyses used below. But, indirect evidence, first of all, an increase in areas consumed by forest fires in northwestern Canada (Gillett et al. 2004) and Alaska (Groisman et al. 2007) suggest a similar development in the northwest of North America.

However, the same analyses had been simultaneously conducted for Canada, Mexico and Russia[13]. The findings of this assessment are as follows:

Over a substantial part of the conterminous U.S. (specifically, over the Eastern U.S. and the southwestern quadrant of CONUS) during the 1967-2006 period, the frequency of occurrence of 30-day-long and above (Eastern U.S.) and 60-day-long and above (Southwest) no-rain periods substantially increased (by 1.1% and 4.3 % per 40 years, respectively). These increases should be compared with average fraction of occurrence of these dry episodes (1.5% and 14% respectively). This means that over the Eastern U.S. the frequency of these episodes nearly doubled. For the Northwestern quadrant of CONUS and the humid Great Lake Area (as well as for adjacent regions of western Canada south of 55°N), for any duration of the dry episodes considered, we did not find statistically significant trends at the 0.05 level (using two- or one-tailed t-tests) in the fraction of the warm season consumed by these episodes.

The observed changes in the occurrence of the prolonged no-rain periods are not restricted to CONUS but are expanded to the adjacent areas of northern and eastern Mexico and southeastern Canada (Groisman and Knight 2007; Figure 5.1.21). Specifically,

Over *northern Mexico*, changes in the duration (in percent of the warm season which is practically the entire year there) of prolonged dry periods 60 or more days without rain has increased by 9.4% during the past 40 years and this increase has been statistically significant (the long-term mean frequency of such dry episode is 49%).

Over *the humid Gulf Coast of Mexico*, there was a statistically significant increase in the frequency of prolonged dry periods, 30 or more days without rain, by 7.3% per 40 years (the long-term mean frequency of such dry episode is 20%). The increase here was mostly defined by a group of dry years in the late 1990s. In 1998, the total duration of prolonged dry periods 30 or more days without rain in this part of Mexico was extremely large, being twofold higher than the average (40% of days annually against the average 20% of days annually). It is worthy to note that this was a year of an extraordinary strong El-Niño.

Over *southeastern Canada*, where precipitation is quite frequent, during the post-World War II period, most of the stations have not seen 30-day intervals without precipitation. Therefore, we lowered the criterion for minimum length of dry episode duration for the region to 20 days. These dry episodes are infrequent occupying on average slightly more than 1% of the warm season (1.2%). Therefore, while a twofold increase in the frequency of dry episodes during the 1967-2005 period (by 1.1%/40yr) is statistically significant at the 0.05 level, practical significance of this change can be questioned.

Over southern Siberia and Russian Far East (Figure 5.1.22 left panel), the frequency of dry episodes above 30 days during the warm season is quite small. This frequency had doubled during the 1956-2005 period. While the duration of the warm season is short (from 4 to 5 months), the mid-summer insolation and maximum temperatures are high. The prolonged no-rain episodes, combined with a general decrease (or no change) in rainfall (cf., Figure 5.1.1, top panel), create a substantial water deficit, increase the forest fire danger (Groisman et al. 2007), and the increase in areas consumed annually by the actual forest fires (Conard et al. 2002; Korovin and Zukkert 2003, updated).

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[13] In Russia, the analyses were conducted only for the regions south of 60°N in the European part of the country and south of 55°N in the Asian Russia for the same reason as for North America (cf., the previous footnote).

The European part of Russia south of 60°N (ER) spans from the taiga zone in the north to dry steppe and semi-deserts in the southeast. The growing season is on average 6 months and in the southern steppes can reach 8 months. The northern part of the region is considered a zone of steady agricultural production while in the south, in the region of the most fertile soils, droughts are frequent. Over this particular part of Russia during the past 60 years precipitation conditions noticeably improved: annual precipitation has increased (Bogdanova et al. 2010), natural runoff of the major river, Volga, has increased (Georgievsky et al. 2002), upper layer soil moisture during the warm season has increased (Speranskaya 2011), and the Palmer Drought Severity Index over the region has increased throughout the 20th century (Dai et al. 2004). However, Figure 5.1.22 (right panel) shows that during the same period of "improvement" in the mean regional hydrological conditions, intra-seasonal variability of rain events remained high and the frequency of prolonged periods without rain has increased. This signal was one of several that preceded a catastrophic drought in July-August 2010. There were drier summers in the past (e.g., 1972 and 2002; Figure 5.1.31) than in 2010. However, in 2010 a strong water deficit due to a prolonged no-rain episode coincided with unprecedented very high surface air temperatures (in 2010, mean July-August surface air temperature over ER was 2°C higher than in the previous record in 1972 and more than 5°C above climatological mean values). In many locations across European Russia absolute temperature records were exceeded, and dramatic thresholds such as "hot nights" were first reported as far north as at 60°N in St. Petersburg. This combination of prolonged no rain period and high summer temperatures decimated crops, caused numerous forest and steppe fires that in some cases spread toward settlements causing property and human life losses (Mokhov 2011). Smog over Moscow affected health of millions citizens and indirectly caused premature deaths (estimated to be of the order of 50,000). Extremely hot nights are harmful for human health when (according to Kalkstein and Davis 1989) the temperature conditions throughout the entire night even into the early morning do not drop below 25.9°C (75°F). They are closely correlated to the increase of detrimental health conditions (heart attacks, strokes, and, when combined with air pollution, with asthma strikes). Over ER such nights are very infrequent (Figure 5.1.23). Therefore, nearly all private houses and apartment buildings are not equipped with air conditioning. However, *ten years prior to the heat spell of 2010 the number of such nights nearly quadrupled*. This change was left unnoticed. Lessons were learned in Western Europe that paid dearly for the heat spell of 2003 but then was much better prepared for the next heat spell of 2006. However a similar scenario was not expected to be relevant for the colder climate of ER and no preparations were made. Therefore, when the 2010 hot spell hit the cities in central ER (including the national capital), the losses, including human life losses were significant.

Such weather conditions were absent during the period of instrumental records and extremely rare during the past millennium. However, for example, all weather anomalies described in old Russian Yearbooks ("Letopisi") for 1092 were repeated in 2010.

During the past 50 years, an increase in precipitation and soil moisture over ER was observed but mostly overlooked were the concurrent changes that at the same time: (a) changes in the extratropical atmospheric circulation became more favorable to the blocking conditions over Northern Eurasia (Mokhov 2011); (b) earlier spring onsets and winter thaws have gradually made a larger fraction of water resources accumulated in the previous seasons unavailable for the next summer season (Bulygina et al. 2011; Groisman et al. 2011); (c) areas affected by agricultural droughts were increasing (Meshcherskaya et al. 2011); (d) frequency of occurrence of prolonged (≥30 days) no-rain periods was increasing (Figure 5.1.22); and (e) the number of days with “very hot” nights with minimum temperatures ≥ 23.9°C became disproportionally large in the past decade. Of course, nobody could predict the size and timing for the Weather Anomaly over ER in 2010 using climate change considerations. However, the ongoing climatic changes (including the severe heat wave outbreaks in Western Europe) staged the scene for it over ER and increased its probability.

Conclusions and Recommendations

In this Chapter we investigated the current state of knowledge about the contemporary changes (mostly during the post-World War II period) of intense precipitation over the global land areas. It looks like these changes in the extratropical land areas were expected from theoretical considerations and their general features have been already reproduced (and projected into the future) by most advanced contemporary global climate models. However, details of these projections differ from model to model and it is not clear what will happen at the boundaries of the regions where these models hint to an increase in both intense precipitation and “drier” conditions. Observations suggest that the area of such regions is significant over the mid-latitudes of the Northern Extratropics and includes a large fraction of the conterminous United States (cf., Figures 5.1. 15 and 5.1.20, 5.1.21; Groisman and Knight 2008), southern Europe and Mediterranean (IPCC 2007; Zolina et al. 2012; Table 5.1.4), and a large swath of the Northern Eurasia forest-steppe and taiga areas (cf., Figures 5.1.1, Table 5.1.2, and Figure 5.1.22; Groisman et al. 2009). How the changing structure of the hydrological cycle in these areas will manifest itself, affect the environment, and human wellbeing is an area of active current studies. In these studies empirical assessments monitoring and trend analyses play an important role. They (a) allow confirmation of theoretical considerations quantifying and refining them and (b) deliver the knowledge about the here and now of the present state of the regional hydrological cycle and its dynamics.

A serious impediment for the studies of long-term changes in intense precipitation is a deficiency of comprehensive data sets of homogeneous time series from dense national meteorological networks available for international use. In the regions where such networks do not exist, we cannot complain because it takes time and resources for their establishment, and decades before they become useful for climate change assessments. But restricted access to the national network data in the regions, where these networks do exist, hampers reliable judgments about the most dangerous component of intense precipitation changes, the changes in the frequency and intensity of damaging extreme rain events. For example, the national precipitation network of Germany consists of more than 4,000 stations (cf., Tomassini and Jacob 2009) while the international (both European and global) archives have only 130 stations. Compared to 2 stations from Poland and 1 station from the Czech Republic, this is a good sample, but any study of rare extreme convective thunderstorms over these countries will be hampered by a danger of delivery of results that are non-representative for Central Europe. It does not help that the Global Precipitation Climatology Center (http://gpcc.dwd.de; Rudolf et al. 2011) most probably has this information (or an access to it) because the Center charter restricts dissemination of the station data to the international science community. The consequences of this impediment are (a) the focus of this Chapter on the regions where we have unrestricted access to precipitation data and (b) an inability of the international scientific community to contribute to assessment of intense precipitation changes in the regions where these changes have occurred, were dramatic, and seriously affected the society. These regions appear on the screen only when something horrible happens (e.g., 2010 flooding in Pakistan). It would be much better if the analyses of intense precipitation changes and their possible consequences were made prior to such events. "*Informed means armed"*.

Final Notes. A few precautions advised to the researchers of intense precipitation changes were presented throughout the Chapter. They include:

There is a relationship between the network density at hand and the upper percentile (absolute rainfall) values whose changes the researcher can access (cf., the discussion on this matter in Groisman et al. 2005, 2012). Both aspects are important. For example, scientists who declare the absence of heavy precipitation changes over the United States using 200 stations (instead of 6000 long-term stations) that are representative for less than 5% of the CONUS territory, are not dissenters or skeptics but simply did not prepare well for their study.

Light precipitation events are not consistently documented with time in many countries (Figure 5.1.11; Groisman et al. 1999). Precautions must be taken to avoid their impact on the artificial changes in the frequency of heavy precipitation. This precaution is especially important for high latitudinal countries (Canada, Russia, and Fennoscandia).

Up to present, most (nearly all) observational results *and* the GCMs projections conveyed the information about changes in the frequency of heavy (sometimes very heavy) precipitation events. This is true even when nearly all climate modelers liberally use the term "extreme" in description of their results. The *request* of the hydrologic and civil engineering communities to advise about changes in frequency and intensity of the actual extreme events (that cause real infrastructure damage and harm to human life) is not yet addressed to satisfaction and is an area of active ongoing studies. Those of these studies that focus on monitoring and documenting changes (i.e., based upon observational data analyses) have a chance to succeed only in the regions with dense networks of long-term meteorological stations available to the national and international scientific communities (cf., achievements described above for the contiguous U.S. in Section **5.1.3c**). Of course, there are other approaches that can be used to address the request of this group of users that include regional high-resolution climate modeling and paleoclimatic and physical boundary considerations. These approaches, however, are beyond the focus of this Chapter.

Summarizing, we conclude that over most of the extratropical land areas in the post-World War II period, increases in the frequency of heavy and very heavy precipitation events have occurred (Figures 5.1.12 through 5.1.17, Table 5.1.4, Section **5.1.3b,c,d**). Over a sizeable part of mid-latitudes at the same time the frequency of the prolonged no-rain periods during the warm period has increased too (Figures 5.1.21, 5.1.22; Zolina et al. 2012). Finally, for the regions with a dense network of long-term precipitation time series, observations support one of the major conclusions of climate modelers (Meehl and Stocker, et al. 2007; Trenberth 2011) about a general increase of precipitation intensity (cf., Figure 5.1.24).

In attempts to project prolonged extreme events (such as droughts and floods) in a given season, climatologists used to look for their precursors in the Earth system "memory" that include anomalies in sea ice (SI) and snow cover extents (SCE), sea surface temperature (SST), and soil moisture and for their patterns (e.g., Southern Oscillation). However the major "memory" component of the Earth system is the Earth Climate System itself. It began changing (IPCC 2007) and is not anymore a constant factor: SST, SI, and SCE anomalies of the past now became "climatology" and it is time to include this new reality in our analyses of the frequency and intensity of extreme events. Apparently, when looking for extreme events occurrence one has to carefully select climatological variables that can be considered as precursors of these events and the changes in mean surface air temperature and precipitation may not be the best among them. Moreover, the characteristics of extreme precipitation and streamflow events that are commonly used in some segments of the scientific community such as maximum annual precipitation (streamflow) values, are not an optimal choice and, in fact may be misleading in the areas where increases in precipitation intensity and prolonged no-rain intervals occur simultaneously. Most of CONUS is one of such regions (cf., Figures 5.1.15, 5.1.17, 5.1.21, and 5.1.24 top panel).

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Figure Captions:

Figure 5.1.1. Top. Summer frequency of rainy days and days with heavy rains over the Asian part of Russia (Sun and Groisman 2000). In this part of the world daily rainfall of 20 mm or above is considered as unusually heavy ("liven") and on average occurs approximately twice during the summer season. B**ottom.** Climatology of wet spells of different duration over Europe (a) climatology; (b) dynamics of changes with time; and (c) linear trends in the fraction of wet days (adapted from Zolina et al. 2010).

Figure 5.1.2. Comparison of intense precipitation characteristics during the June-November season over the Southeastern U.S. associated with tropical cyclones (TC) for the 31 years of warmest and coldest Northern Hemisphere temperatures during the 1948-2009 period (top) and other not-associated with TC intense rainfall (bottom). Estimates of precipitation characteristics for these 31-yr periods were averaged and their ratios (in percent per station) are shown sorted by day rainfall intensity ranges. The comparison shows that while the heavy rainfall characteristics associated with TC (up to extreme daily rain events above 154.9 mm) have increased over the southeastern United States during the last three decades, intense rain totals of other genera decreased (archive of Groisman et al. 2012).

Figure 5.1.3. Changes with time, past three decades (1979-2009) versus previous period (1948-1978) of the fraction of "moderately heavy" precipitation (from 12.7 to 25.4 mm; or 0.5 inch to 1 inch) among all intense daily rain events above 12.7 mm over the contiguous U.S. Fraction of moderately intense precipitation within the intense precipitation spectra is decreasing over most of the contiguous U.S. (CONUS) Annually among all daily rain events over CONUS, "intense" events (i.e., above 12.7 mm) comprise 25% of all days with precipitation but deliver more than 70% of rainfall. Among all intense events, days with moderately heavy precipitation are a majority (~75%) and deliver slightly more than a half of precipitation totals. Figure shows that the fraction of moderately intense precipitation within the intense precipitation spectra is decreasing over most of the contiguous U.S. (archive of Groisman et al. 2012). At the same time, very heavy precipitation is increasing over the eastern two/thirds of CONUS (Groisman et al. 2004; USCCP 2009).

Figure 5.1.4. Global and Arctic surface air temperature changes (upper panels; Lugina et al. 2006 updated) and associated with them SCE and SI changes (bottom panels; NOAA 2011; NSIDC 2011). We show here global (90°S to 90°N) time series since 1957 (i.e., since the First International Geophysical Year). Other geographical zones of the globe (north of 60°S) are better monitored and their temperature variations can be reported for the past 130 years (the period of massive network of instrumental in situ observations. Hemispheric SCE and SI changes are based on satellite observations.

Figure 5.1.5. Mean seasonal area-averaged number of days over CONUS with maximum daily CAPE above 1500 J kg^{-1}. Spring and Summer. Archive of the North American Regional Reanalysis (NARR).

Figure 5.1.6. Seasonal changes in the number of days with W- and C-types of atmospheric circulation. The W-type days are increasing in the past 60 years in the cold season and in the past 40 years in warm season. The C-type days frequency does not appreciably change in the cold season but systematically decreased during the entire 20th century in the warm season. The E-type days are not shown because they complement the W- and C-type days (in the Wangengheim

– Girs classification there are only a handful of situations (<1%) when the types were not assigned to a particular day of the year).

Figure 5.1.7. Upper panels. May-July surface air temperature linear trends, (left) 1950-2011 and right (1970-2011) periods. US daily cooperative network data used for this analysis were bias-adjusted using the algorithm proposed by Menne et al. (2009). **Bottom panels**. Changes of the number of days with heavy rainfall (D, blue dots) for the warm season (April through October; left panel) and for the major part of growing season (May-July; right panel) regionally averaged over Midwest and mean seasonal maximum temperatures, T_{max} (red dots).

Figure 5.1.8. Core Midwest States (Illinois, Indiana, and Iowa). Areas with corn (left) and soy beans (right) harvested, %, and yield (liter m^{-2}) related to the total states area.

Figure 5.9. (a) Maps indicating the density of stations that have at least 10 years of precipitation records during the past successive 30-year intervals (source: http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/). (b) Two station networks with long-term precipitation time series of hourly and daily precipitation available for the past 60 years over the contiguous United States. Blue dots on the maps show distribution of 3076 HPD stations (left) and 5885 long-term daily cooperative observer (COOP) stations (right). Adapted from Groisman et al. (2004, 2012). Boundaries of regions used for area-averaged climatologies and change analyses in these studies are also shown. (c) Stations used in the recent near-global assessment of changes in intense precipitation (Alexander et al. 2006). Colors in this map are used to show the stations with daily precipitation from different sources. The largest of these sources (black dots) is GHCN-daily. Total number of stations is 5948.

Figure 5.1.10. Major instrument and/or methodology changes at the national precipitation network of several countries of the Northern Hemisphere and average order of biases (inhomogeneities) caused by these changes (Karl et al. 1993, updated).

Figure 5.1.11. **Top panel**. Mean number of days with non-zero very light daily precipitation over the conterminous United States (left; Groisman and Knight 2007, 2008) and along the 2.5-degree latitudinal belt along the U.S. - Canadian border, U.S. (center) and Canadian (right) sides of the border. **Middle panels.** Annual number of days across the US Canadian border (±2.5° lat.) with precipitation (left) above 0.31 mm and (right) above 2.31 mm. Blue and red dots show the US and Canadian precipitation frequency respectively. Note the difference in trends, first of all, for Canada. **Bottom panels.** Annual number of days across the US Canadian border (±2.5° lat.) with heavy precipitation (upper 10%-ile; left) and precipitation totals for days with P above 0.31 mm (right). Blue and red dots show the US and Canadian precipitation frequency respectively.

Figure 5.1.12. 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. 2000, Groisman et al. 2005, substantially updated first in Trenberth, Jones et al. 2007 and for the present Chapter). 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 5.1.13. Frequency of very heavy (above the upper 0.3 percentile) annual (blue) and summer (dark red) daily precipitation events during the 1950-2011 period over Fennoscandia.

All linear trends (shown by dashed lines) are statistically significant at the 0.01 level or above (updated time series from Groisman et al. 2005). Mean regional numbers were produced by the arithmetic averaging of the actual stations' numbers of days with very heavy precipitation within the 1ºx1º grid cells with the appropriate area-weights averaging of the grid cell values.

Figure 5.1.14. Heavy and very heavy annual precipitation variations and linear trends along the northwestern coast of North America (a) British Columbia south of 55°N and (b) Alaska south of 62°N. Statistical significance of linear trends is provided in Table 5.1.3. Mean regional numbers were produced by the arithmetic averaging of the actual stations' numbers of days with heavy and very heavy precipitation within the 1ºx1º grid cells with the appropriate area-weights averaging of the grid cell values.

Figure 5.1.15. Observed increases in very heavy precipitation during the 1958-2010/11 (update of similar finding presented in USCCSP 2009). *Left*. Percent increases in the annual amount falling in very heavy rain events defined as the heaviest 1 percent of all daily events from 1958 to 2010 for each region of the United States. Changes in the Eastern half of the nation are statistically significant at the 0.05 or higher levels and over the Great Plains, at the 0.1 level. *Right*. Percent increases in the amount falling in very heavy rain events defined as the heaviest 1 percent of all daily events from 1958 to 2011 in the summer season for each region of CONUS. Changes over the north-central and north-eastern parts of the nation are statistically significant at the 0.01 and 0.05 levels respectively; all other trends are insignificant.

Figure 5.1.16. Comparison of intense precipitation days (upper line of plots) and multi-day intense precipitation events (lower plots) over the central U.S. for 1979-2009 and 1948-1978 periods sorted by day/event intensities (in mm). Estimates of precipitation characteristics for these 31 year periods were averaged and their ratios (in percent per station) are shown for HPD (left) and COOP (right) networks.

Figure 5.1.17. **Top panel**. Mean intense precipitation, mm, per event that comes with 1-day- and 2-day-long events over the contiguous U.S. The estimates are based upon all intense events above 12.7 mm at ~6,000 long-term U.S. cooperative stations for the 1948-2011 period (Archive of Groisman et al. 2012). **Bottom panel**. The same but for 3-day- and 4-day-long events over the Midwestern U.S.

Figure 5.1.18. Same as Figure 5.1.16 but for daily precipitation events (COOP network) over the northwestern (Washington, Oregon, and Idaho; left) and southwestern (Four Corners; Utah, Colorado, Arizona, and New Mexico; right) United States.

Figure 5.1.19. Precipitation duration in the extratropics estimated by recording gauges in Northern Eurasia (Lebedev 1964) and the United States (archive of Groisman et al. 2012). Only intense daily events (>12.7 mm) are considered for the contiguous U.S.

Figure 5.1.20. Comparison of heavy rainfall characteristics in the "warm" and "cold" Northern Hemisphere years in the eastern half of the contiguous U.S. (east of the Mississippi River). Data of 1,715 Hourly Precipitation (HPD) stations for the 1948-2007 period were used in this comparison. Warm and cold years rainfall records were scaled to the same number of stations available in both 30-year-long periods with the difference in the mean annual surface air temperature, ΔT_{NH}, equal to 0.54°C. Heavy daily rainfall events are sorted by the rainfall totals in the same manner as in Figures 5.1.2 and 5.1.16 but the x-axes is in inches.

Figure 5.1.21. Schematic summary of statistically significant results showing the increase of prolonged dry day episodes across North America during the 1967-2006 period. Dots show the station locations with daily rainfall and temperature data used in the analysis and the dot colors

(and solid lines) outline the regional boundaries within which the authors evaluated regional estimates of no-rain periods (Groisman and Knight 2007, 2008).

Figure 5.1.22. Dry episodes above 30 days during the warm season over (**left**) Asian Russia east of 85°E and south of 55°N and (**right**) European Russia south of 60°N. Both linear trends are statistically significant at the 0.05 level.

Figure 5.1.23. Number of days with "hot" nights (when minimum daily surface air temperatures remain above 23.9°C) area-averaged over ER south of 60°N during the 1891-2009 period. This number for 2010 exceeds 5. These days closely correlate with an increased mortality of unprotected population.

Figure 5.1.24. Top. Mean daily precipitation, mm, per event that comes with 1-day- and 2-day-long events over the contiguous U.S. The estimates of precipitation intensity in 1-day-long (P_1, mm day^{-1}) and two-day-long (P_2, mm (2 days)$^{-1}$) are based upon all precipitation events above 0.5 mm at ~6,000 long-term U.S. cooperative stations during the 1948-2011 period (Updated archive of Groisman et al. 2012). P_1 and P_2 were selected to be non-overlapping events (1-day events are not included in the 2-day events) and together contribute approximately 60% of nation precipitation totals. **Bottom.** Mean summer (JJA) rainfall intensity, mm d^{-1} over Japan. Estimates of the annual precipitation intensity over the country also show an increase (with the mean rate of 14%/50yr) but are not presented here due to our concerns about the instrumental homogeneity of the cold season precipitation measurements in this country after introduction of automation (tipping bucket rain gauges) in early 1970s and thereafter.

Table 5.5.1. Different definitions of precipitation events at the upper end of its distribution (fitted to the eastern two thirds of the conterminous U.S. territory). Decimal points are introduced to accommodate the British Empire Unit System (inches) used in the U.S. meteorological practice instead of the SI-System.

Term used to describe a precipitation event at upper end of its distribution	Daily and multi-day precipitation events with the totals above (or within) selected thresholds based upon	
	absolute values	upper percentiles
Above 10 mm[14]	Above 10 mm	n/a
Intense	above 12.7 mm	Above the upper 25%
Heavy	[12.7 mm 76.2 mm]	Upper 10 to 5%
Annual maximum event total[15]	from 10 mm to 300 mm	~ the upper 1%; may vary broadly
Moderately heavy	[12.7 mm 25.4 mm]	n/a
Very heavy	Above 75 mm	Above the upper 1%
Extreme	Above 150 mm	Above the upper 0.1%

[14] This characteristic (threshold) was introduced by Frich (1999) for global assessments of “extreme” precipitation. It can be used in cold climates (e.g., in the Arctic) where totals above 10 mm are indeed rare.
[15] This characteristic is commonly used in the hydrological and civil engineering communities.

Table 5.1.2. Trend characteristics of the summer precipitation for the western part of the Russian Federation over the period 1936-2010. Mean totals and the number of days with precipitation above upper percentile thresholds. Trend values statistically significant at the 0.05 level or at the 0.01 level are marked with asterisks (*) and double asterisks (**) respectively (updated archive of Groisman et al. 2005).

Precipitation		***Mean Values***	***Thresholds, (Thr.) mm***	***Number of days with P > Thr. Linear trend and its variance***	
				%/50yr	***%***
		North of European Russia (north of 60ºN)			
Total, mm		**190**	**0.5**	**12**	**9****
Heavy, days	**90%-ile**	**3.4**	**7**	**17**	**9****
	95%-ile	**1.7**	**11**	**24**	**11****
Very heavy,	**99%-ile**	**0.36**	**23**	**13**	**1**
Extreme,	**99.7%-ile**	**0.12**	**33**	**-**	**0**
		European part of the Russian Federation south of 60ºN			
Total, mm		**180**	**0.5**	**9**	**6 ****
Heavy, days	**90%-ile**		**6**	**14**	**10****
	95%-ile	**1.4**	**11**	**19**	**9****
Very heavy,	**99%-ile**	**0.29**	**25**	**14**	**3**
Extreme,	**99.7%-ile**	**0.10**	**38**	**18**	**3**

Table 5.1.3. 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.

Region, Period assessed	**Total precipitation Mean mm**	**Total precipitation Trend %/50yr**	**95%-ile threshold Value mm**	**95%-ile threshold Trend %/50 yr**	**99.7%-ile threshold Value mm**	**99.7%-ile threshold Trend %/50 yr**
British Columbia, south of 55º N 1910-2010	1,625	6.1**	26	12**	56	16**
Alaska, south of 62º N 1950-2010	1,635	6.8*	28	13*		17

Table 5.1.4. Characteristics of changes in heavy and very heavy precipitation across the global land areas depicted in Figure 5.1.12. All statements about statistical significance are based upon 0.05 or higher levels of significance. Abbreviation "P" is used for precipitation.

Region	Season	Period	Characteristics of intense P	Sign of the change	Comments	Sources
Japan						
All nation	Annual	1890-1990	Years of 3 max. daily P per century	Increase	First report.	Iwashim
North of 37.5°N South of 37.5°N	JJA JJA	1951-1989	Above 100 mm d^{-1}	Increase Decrease		Easterli
North, South, and all nation	Annual & JJA	1951-2011	Upper 0.3% of rain events Daily intensity	No Change Increase	Significant decreases in precipitation totals and rain days are accompanied with no change or a weak increase in heavy and very heavy daily rain events. Nationwide precipitation intensity has increased by 12 to 15 %/50yr.	Groisma
All nation	Annual 4 seasons	1898-2003	Upper 10% of 4-hourly events	Increase	A century long increase by ~30%	Fujibe e
China						
Northeast Southeast	JJA JJA	1951-1997 1951-1997	Above 50 mm d^{-1} Above 100 mm d^{-1}	Decrease Increase	Reported changes were statistically insignificant	Easterli
North West Southeast Mid–lower reaches of the Yangtze River	Annual, warm, & cold; 4 seasons	1951-2000 1960-2001	Upper 5% of rain events (upper 2.5% and 5% in Wang and Zhou)	Decrease Increase Increase Increase		Zhai et a 2005
Tibetan Plateau	Annual	1961-2005	Frich indices	Increase	Decrease in the central Plateau	You et a
India						
Western half	Annual and JJAS	1901-1983 1910-2000	Above 100 mm Upper 10%, 5%, & 2.5% of rain events Max 1,5, 30 day ∑	Increase Increase	 Decrease in the eastern half Nationwide increases outnumber decreases by 2 to 1	Easterli Roy and
West coast and Maharashtra		1901-2000	Above 75, 125 mm d^{-1}, annual maxim.	Increase		Joshi an
Central Region Central Region		1951-2000 1901-2004	Daily events above 100 and 150 mm	Increase Increase	Statistically significant Statistically significant	Goswan Rajeeva
Other Asian countries and regions						
Middle East	Annual	1950-2004	Frich indices	No change		Zhang e 2005
Central Asia North. Pakistan Sri Lanka	Annual	1961-2000	Frich indices; Max. 5-day rainfall totals	No change Increase Decrease	 Statistically significant Statistically significant	Klein Ta
Thailand Indochina	SON Annual	1951-1985 1971-2005	Above 100 mm d^{-1} Frich indices	Decrease No change	 No coherent changes were	Easterli Caesar e

& Indonesia		1961-1998			found over the region	Manton
Australia						
N.S.Wales&Vic.	DJF	1900-1996	Above 50.8 mm d^{-1}	Increase	Strong and significant	Easterli
Southwestern tip of the continent	JJA	1913-1998	Upper 0.3% of rain events	Decrease	Significant only at the 0.1 level	Groisma
Continent except the desert areas	Nov-Apr May-Oct	1910-1990	Upper 10% and 5% of rain events	Increase Increase	But decrease in the Southwest Insignificant change	Suppiah
East &Southeast Southwestern tip	Annual	1910-1998	Upper 5% of rain events	Increase Decrease	Strong and significant	Haylock .
Sub-Sahara Africa						
Ethiopia&Eritrea Kenya and Tanzania	JJA MAM	1951-1987 1940-1967	Above 25.4 mm d^{-1} Above 50.8 mm d^{-1}	Decrease Decrease	Decreases were statistically significant and strong	Easterli
Northern Nigeria	JJAS	1931-1996	Above 25 mm d^{-1}	Decrease	Decrease after a change point, mostly between 1964 and 1972	Tarhule
Sahel zone Guinea, Conakry D. Rep. Congo Zimbabwe	Annual Annual Annual Annual	1961-1990 1955-2006 1955-2006 1955-2006	Maximum annual 5-day rainfall; Frich indices	Decrease Decrease Decrease Increase	Statistically significant	Easterli Aguillar
South Africa						
Southwest	JJA	1926-1997	Above 25.4 mm d^{-1}	Increase	Strong and significant	Easterli
Natal	DJF	1901-1997	Above 50.8 mm d^{-1}	Increase	Strong and significant	
Eastern half of the nation	Annual & DJF	1906-1997	Upper 0.3% of rain events	Increase	Strong and significant	Groisma
Entire nation	Annual	1931-1990	10yr return max. P In two 30yr periods	Increase	Significant increase over ~70% of the country	Mason e
				Increase	Overview; No original analyses	Faucher
Central America	Annual	1961-2003	Frich indices	Increase		Aguillar
Caribbean	Annual	1958-1999	Frich indices	Increase		Peterson
Brazil						
Nord-Este	MAM	1935-1983	Above 100 mm d^{-1}	Increase		Easterli
Nord-Este North.Subtropics South &Uruguay	Annual Annual Annual	1911-2001 1941-2001 1941-2001	Upper 0.3% of rain events	Increase Increase Increase	Increases in both regions of Eastern Brazil were strong and statistically significant.	Groisma
South& Uruguay & Paraguay	Annual	1960-2000	Number of days with P> 10 mm	Increase	Statistically significant trends around the La Plata Basin	Mareng
Southeast South	Annual Annual	1960-2004	Upper 1% and 0.1% of rain events	Increase Increase	Trend is insignificant Statistically significant trend	Teixeira
South America beyond Brazil						
Ecuador Peru & Chile North Argentina	Annual	1960-2000	Frich indices for intense rainfall	Increase Decrease Increase	Different indices give opposite signs along the Pacific Coast.	Haylock
La Plata Basin	Four seasons	1950-2000	Upper 25% of rain events	Increase	Increase in all seasons except the austral winter (JJA)	Penalba
Central Europe and Mediterranean						
Czech Rep.	Annual	1895-2006	Maximum daily P.	No change		Květoň
	DJF MAM	1961-2005	Max 1,3,5, 10, 20 daily totals; P in	Increase Decrease	Increase is mostly in the West	Kyselý

	JJA SON		the upper 10% and 5% of rain events	Increase No change	Weak increase	
Austria	Annual	More than 50 years of data	Max daily P; upper 5 %, 1%, and 0.5% of rain events	No change	Among 31 analyzed stations, 20 had ≤ 70 years of data and 6 had ≥ 100 years	Villarin
Switzerland	Autumn Winter	1901-1994	Events with return period $\geq$30 days	Increase		Frei and
United Kingdom	DJF JJA DJF	1961-2001 1961-2000 1958-2000	Days with P ≥ 15 mm Max. 5-day rainfall	Increase Decrease Increase		Osborn Haylock
Northern Europe S. west & S. east Europe south of 60°N All continent West of 60°E; mostly central North & Central. Mediterranean North & Central South Poland, Thuringia, and Saxony	DJF DJF All but JJA Annual JJA DJF Oct-Mar Apr-Sep Annual, seasonal	1958-2000 1958-2000 1958-1975 1976-2000 1946-1999 1901-2000 1950-2009 1951-2006	Upper 10% events Upper 10% events Above 60 mm d^{-1} Above 60 mm d^{-1} Above 20 mm d^{-1} and upper 5% days Frich indices of heavy precipitation Duration of wet periods Upper 5% and 10% precipitation events	Increase Decrease Decrease No change Increase Increase Increase Increase Decrease Variable, regionally seasonally	The trends were calculated on a station basis Statistically significant Insignificant decrease No increase in Southern Europe Weak average increase Statistically significant But increase in France and Benelux nations Over Germany: increase Over southern Poland: mostly decrease, especially in JJA	Haylock Karagia Klein Ta Moberg Zolina e Łupikas
France Southern France	2 seasons Annual	1960-2003 1949-2004	Annual daily maximum P	Increase Increase	Results are inconclusive. Statistically significant trend	Cantet e Neppel
Spain Spain, Catalonia	Annual Annual Winter Spring	1951-1995 1930-2006	Above 128 mm d^{-1} 10-yr return period quantile	Increase No change Decrease Increase	Statistically significant	Alpert e Beguier
Italy	Annual	1951-1995 1880-2002	Above 128 mm d^{-1} Daily intensity. Upper 1% of daily events.	Increase Increase Increase	Statistically significant Increase only in the North	Alpert e Brunetti
Greece	Cold season	1950-2000	Upper 5% of rain events	Increase		Norrant
Israel North Israel South Israel	Annual	1951-1995 1930-1990	Above 64 mm d^{-1} Shape parameter of the Γ-distribution	No change Decrease Increase	Land use change may cause some of these changes	Alpert e Ben Gai

Table 5.1.5. Climatology of the intense precipitation in the northwestern and southwestern (Four Corners) United States.

	Northwest, NW		NW, west of 121.5°W	Four Corners	
Precipitation Range, mm	Days with P yr^{-1} stn^{-1}	Percent of events	Days with P yr^{-1} stn^{-1}	Days with P yr^{-1} stn^{-1}	Percent of events
12.7 - 25.4	14.45	78.7	27.6	6.037	86.1
27.9 – 50.8	3.187	17.3	7.2	0.8683	12.4
53.3 - 76.2	0.5449	3.0	1.3	0.0884	1.26
78.7 - 101.6	0.1296	0.706	0.306	0.0156	0.223
104.1 -127	0.0378	0.206	0.0914	0.0032	0.046
129.5-152.4	0.0119	0.065	0.0287	0.0008	0.011
>154.9	0.0093	0.051	0.0198	0.0004	0.005
All days with intense P	18.37	100	36.50	7.014	100

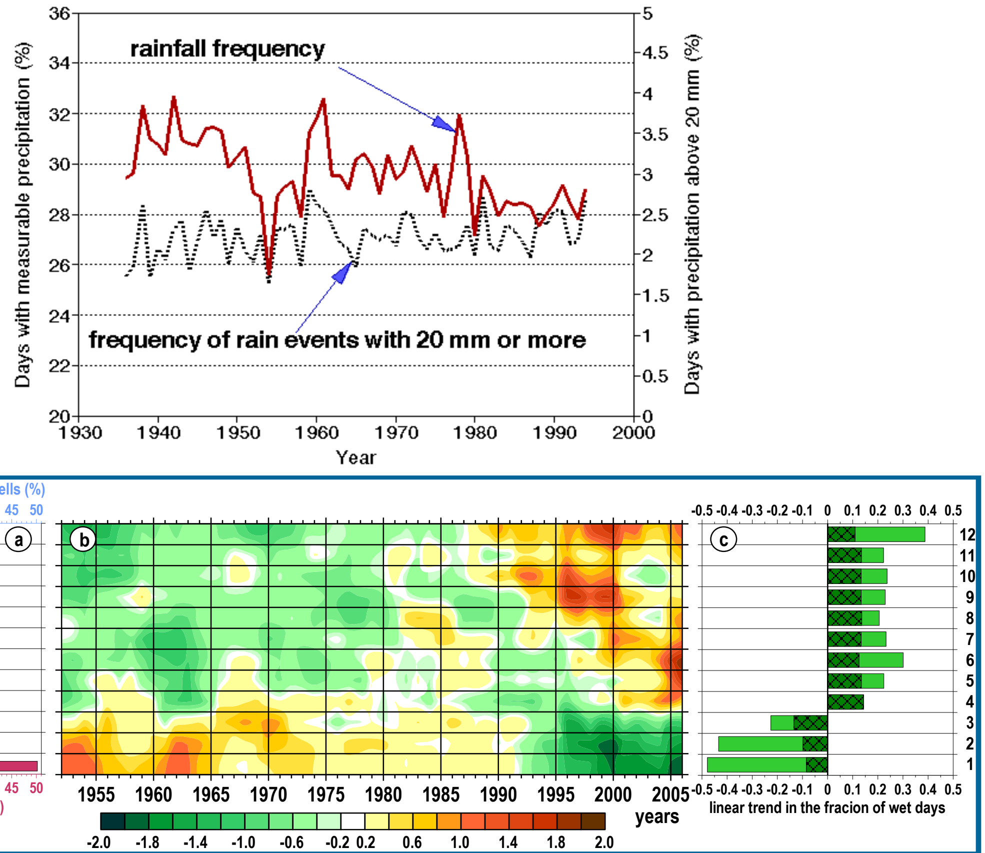


Figure 5.1.1. Top. Summer frequency of rainy days and days with heavy rains over the Asian part of Russia (Sun and Groisman 2000). In this part of the world daily rainfall of 20 mm or above is considered as unusually heavy ("liven") and on average occurs approximately twice during the summer season. **Bottom.** Climatology of wet spells of different duration over Europe (a) climatology; (b) dynamics of changes with time; and (c) linear trends in the fraction of wet days (adapted from Zolina et al. 2010).

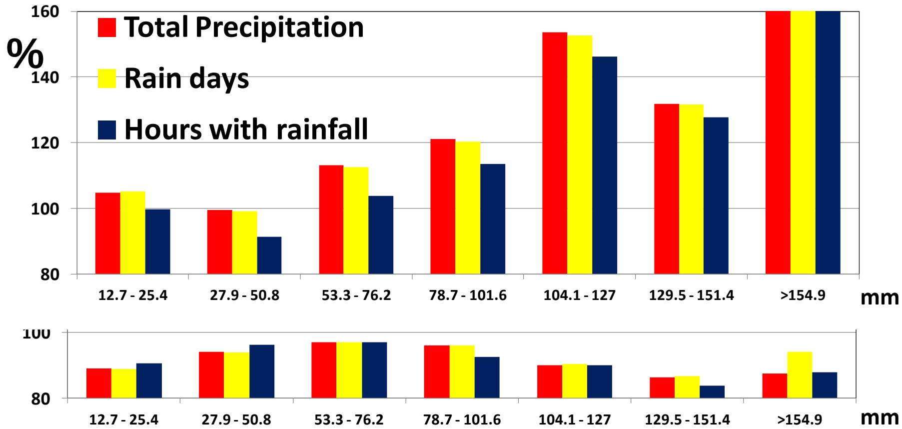


Figure 5.1.2. Comparison of intense precipitation characteristics during the June-November season over the Southeastern U.S. associated with tropical cyclones (TC) for the 31 years of warmest and coldest Northern Hemisphere temperatures during the 1948-2009 period (top) and other not-associated with TC intense rainfall (bottom). Estimates of precipitation characteristics for these 31-yr periods were averaged and their ratios (in percent per station) are shown sorted by day rainfall intensity ranges. The comparison shows that while the heavy rainfall characteristics associated with TC (up to extreme daily rain events above 154.9 mm) have increased over the southeastern United States during the last three decades, intense rain totals of other genera decreased (archive of Groisman et al. 2012).

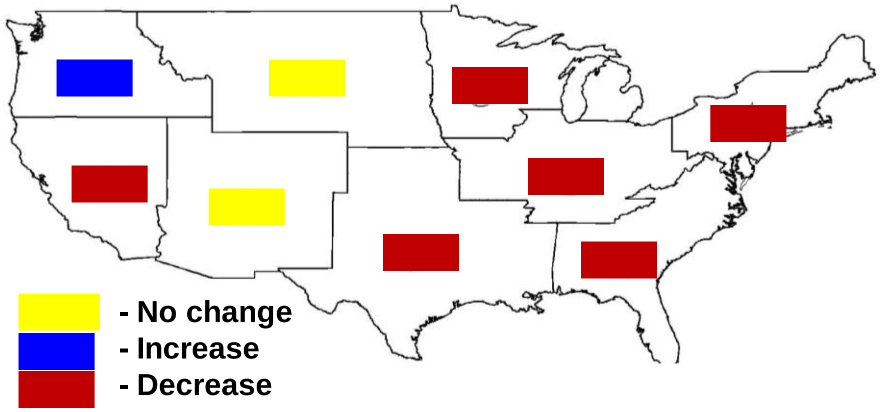


Figure 5.1.3. Changes with time, past three decades (1979-2009) versus previous period (1948-1978) of the fraction of "moderately heavy" precipitation (from 12.7 to 25.4 mm; or 0.5 inch to 1 inch) among all intense daily rain events above 12.7 mm over the contiguous U.S. Fraction of moderately intense precipitation within the intense precipitation spectra is decreasing over most of the contiguous U.S. (CONUS) Annually among all daily rain events over CONUS, "intense" events (i.e., above 12.7 mm) comprise 25% of all days with precipitation but deliver more than 70% of rainfall. Among all intense events, days with moderately heavy precipitation are a majority (~75%) and deliver slightly more than a half of precipitation totals. Figure shows that the fraction of moderately intense precipitation within the intense precipitation spectra is decreasing over most of the contiguous U.S. (archive of Groisman et al. 2012). At the same time, very heavy precipitation is increasing over the eastern two/thirds of CONUS (Groisman et al. 2004; USCCP 2009).

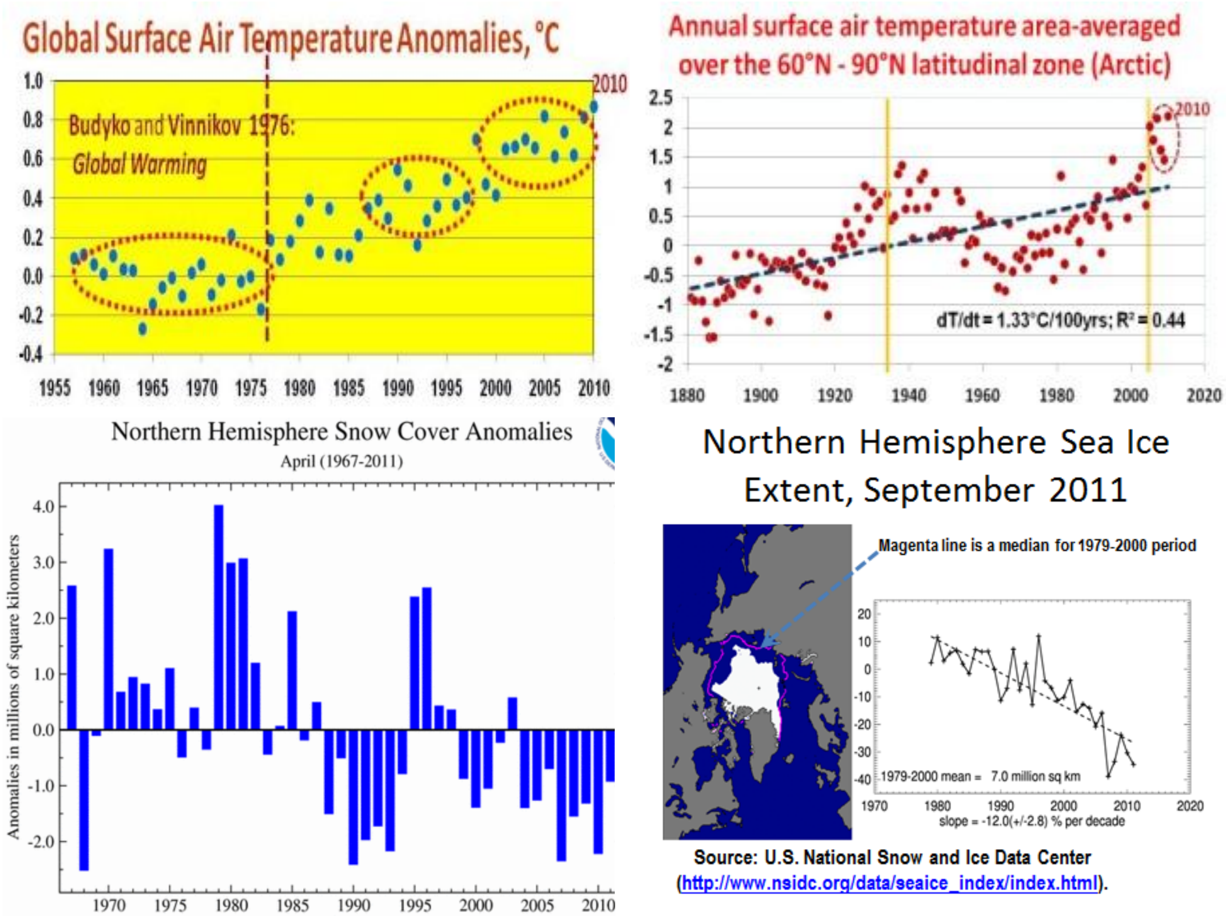


Figure 5.1.4. Global and Arctic surface air temperature changes (upper panels; Lugina et al. 2006 updated) and associated with them SCE and SI changes (bottom panels; NOAA 2011; NSIDC 2011). We show here global (90°S to 90°N) time series since 1957 (i.e., since the First International Geophysical Year). Other geographical zones of the globe (north of 60°S) are better monitored and their temperature variations can be reported for the past 130 years (the period of massive network of instrumental in situ observations. Hemispheric SCE and SI changes are based on satellite observations.

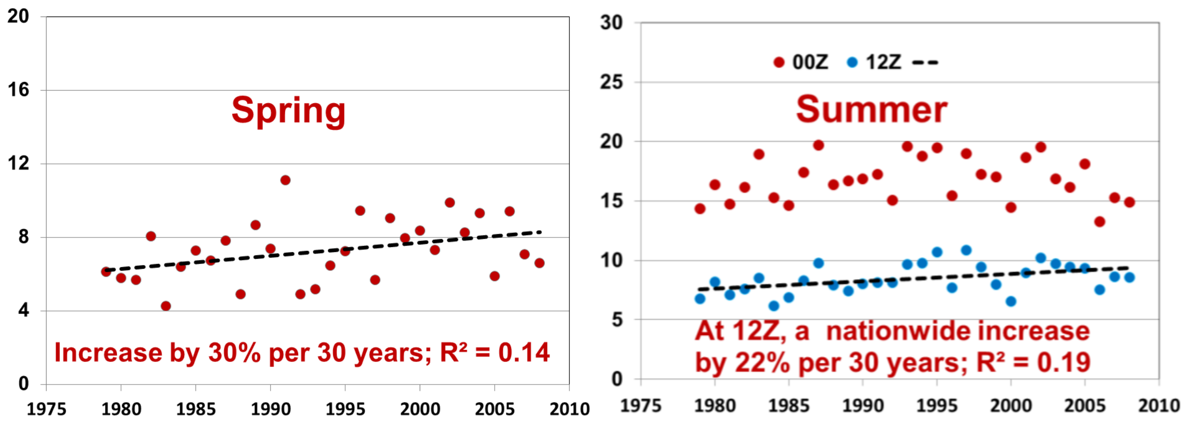


Figure 5.1.5. Mean seasonal area-averaged number of days over CONUS with maximum daily CAPE above 1500 J kg^{-1}. Spring and Summer. Archive of the North American Regional Reanalysis (NARR).

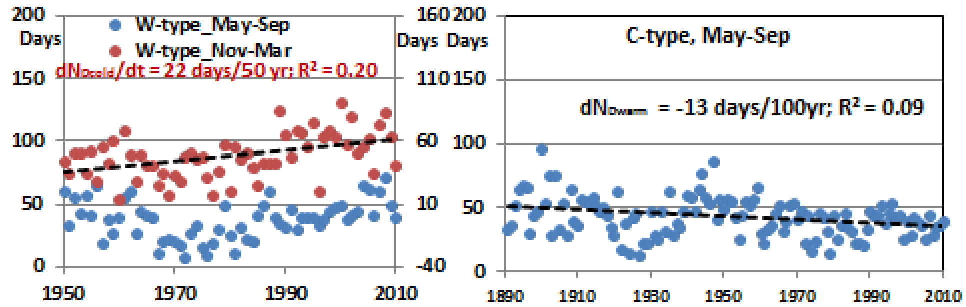


Figure 5.1.6. Seasonal changes in the number of days with W- and C-types of atmospheric circulation. The W-type days are increasing in the past 60 years in the cold season and in the past 40 years in warm season. The C-type days frequency does not appreciably change in the cold season but systematically decreased during the entire 20th century in the warm season. The E-type days are not shown because they complement the W- and C-type days (in the Wangengheim – Girs classification there are only a handful of situations (<1%) when the types were not assigned to a particular day of the year).

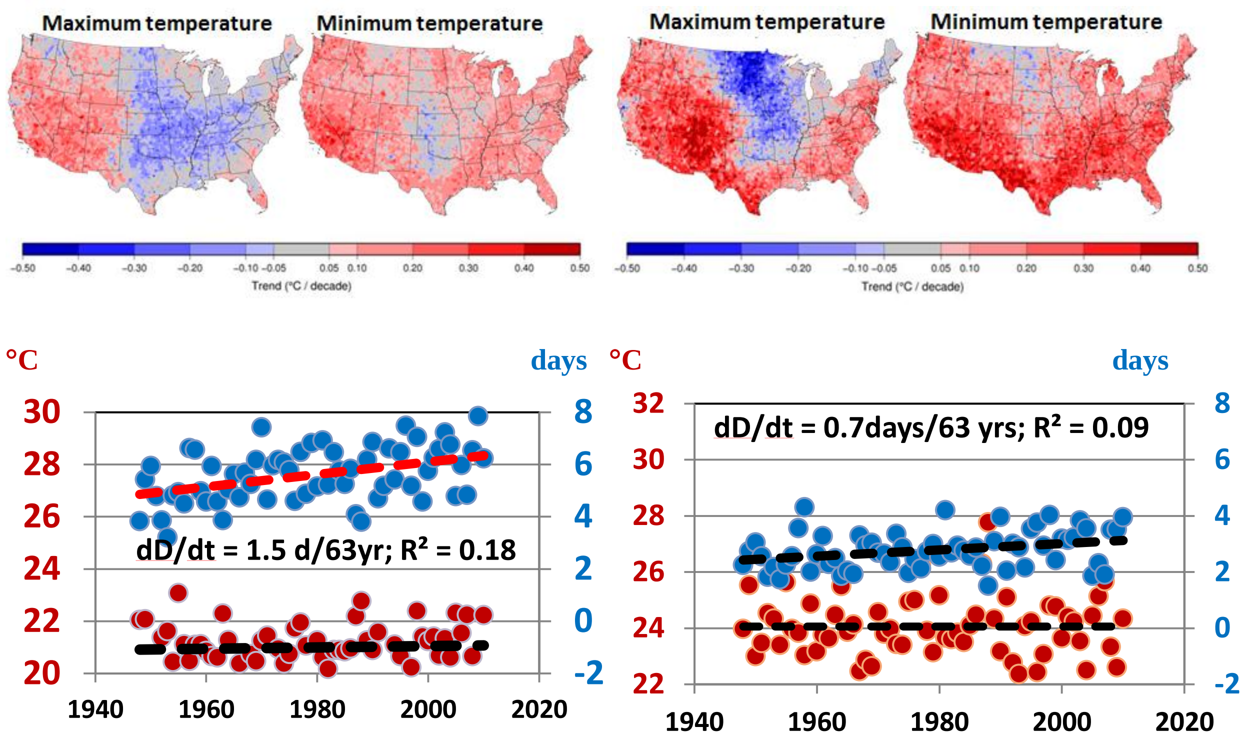


Figure 5.1.7. Upper panels. May-July surface air temperature linear trends, (left) 1950-2011 and right (1970-2011) periods. US daily cooperative network data used for this analysis were bias-adjusted using the algorithm proposed by Menne et al. (2009). **Bottom panels**. Changes of the number of days with heavy rainfall, (D, blue dots) for the warm season (April through October; left) and for the major part of growing season (May-July; right) regionally averaged over Midwest and mean seasonal maximum temperatures, T_{max} (red dots).

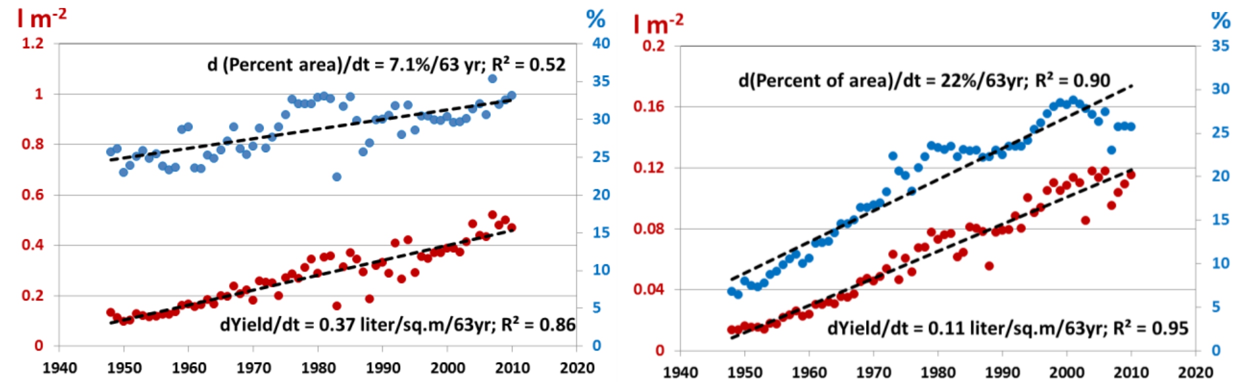


Figure 5.1.8. Core Midwest States (Illinois, Indiana, and Iowa). Areas with corn (left) and soy beans (right) harvested, %, and yield (liter m^{-2}) related to the total states area.

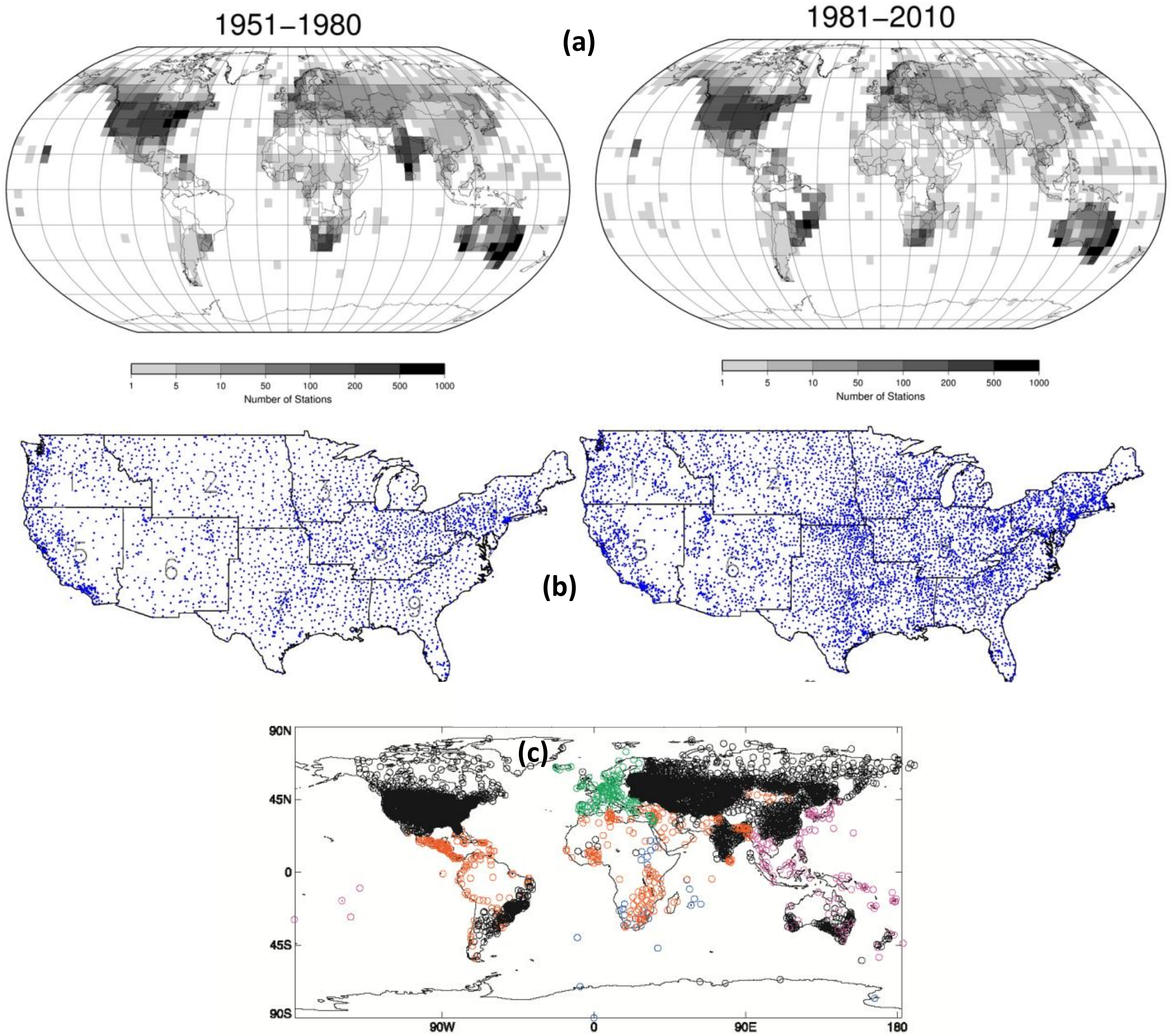


Figure 5.9. (a) Maps indicating the density of stations that have at least 10 years of precipitation records during the past successive 30-year intervals (source: http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/). (b) **.** Two station networks with long-term precipitation time series of hourly and daily precipitation available for the past 60 years over the contiguous United States. Blue dots on the maps show distribution of 3076 HPD stations (left) and 5885 long-term daily cooperative observer (COOP) stations (right). Adapted from Groisman et al. (2004, 2012). Boundaries of regions used for area-averaged climatologies and change analyses in these studies are also shown. (c) Stations used in the recent near-global assessment of changes in intense precipitation (Alexander et al. 2006). Colors in this map are used to show the stations with daily precipitation from different sources. The largest of these sources (black dots) is GHCN-daily. Total number of stations is 5948.

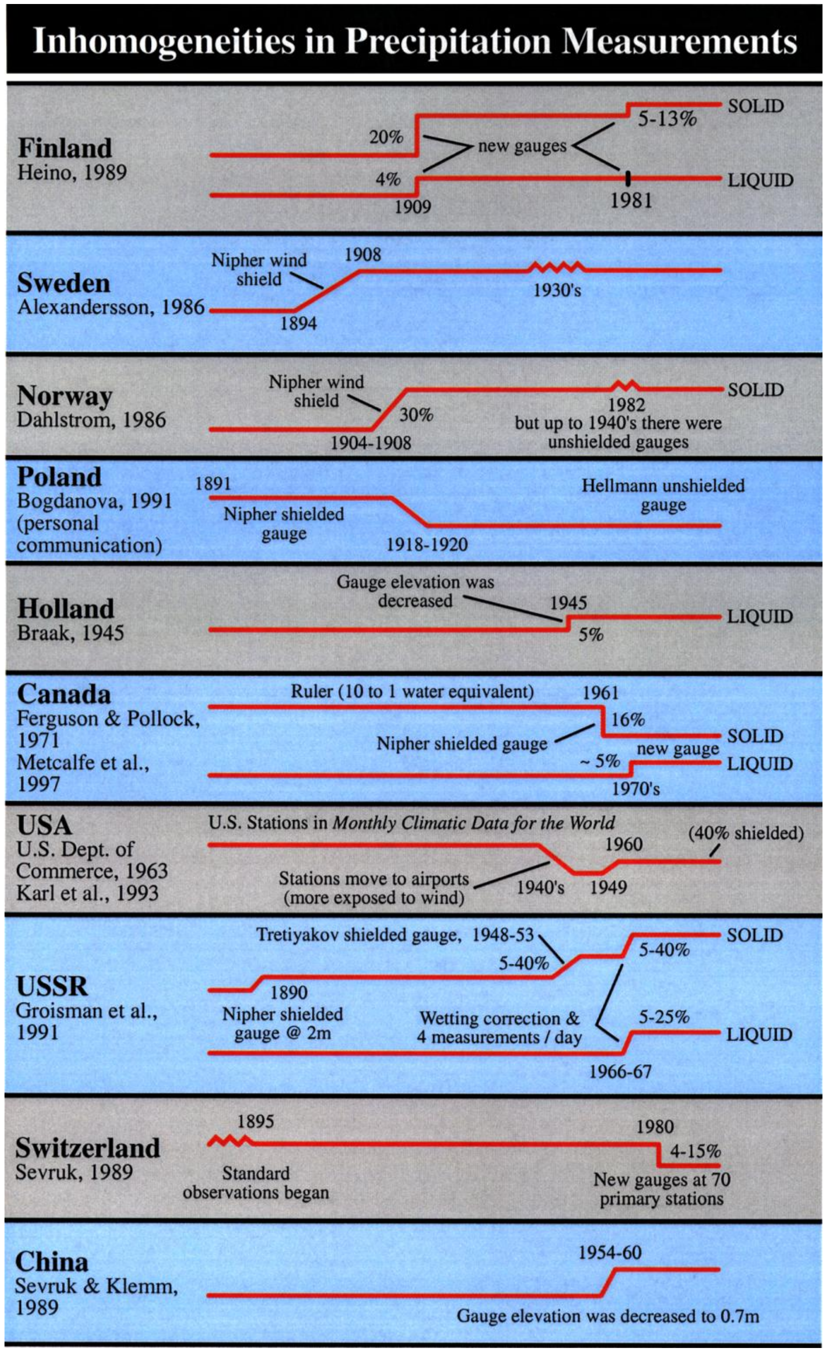


Figure 5.1.10. Major instrument and/or methodology changes at the national precipitation network of several countries of the Northern Hemisphere and average order of biases (inhomogeneities) caused by these changes (Karl et al. 1993, updated).

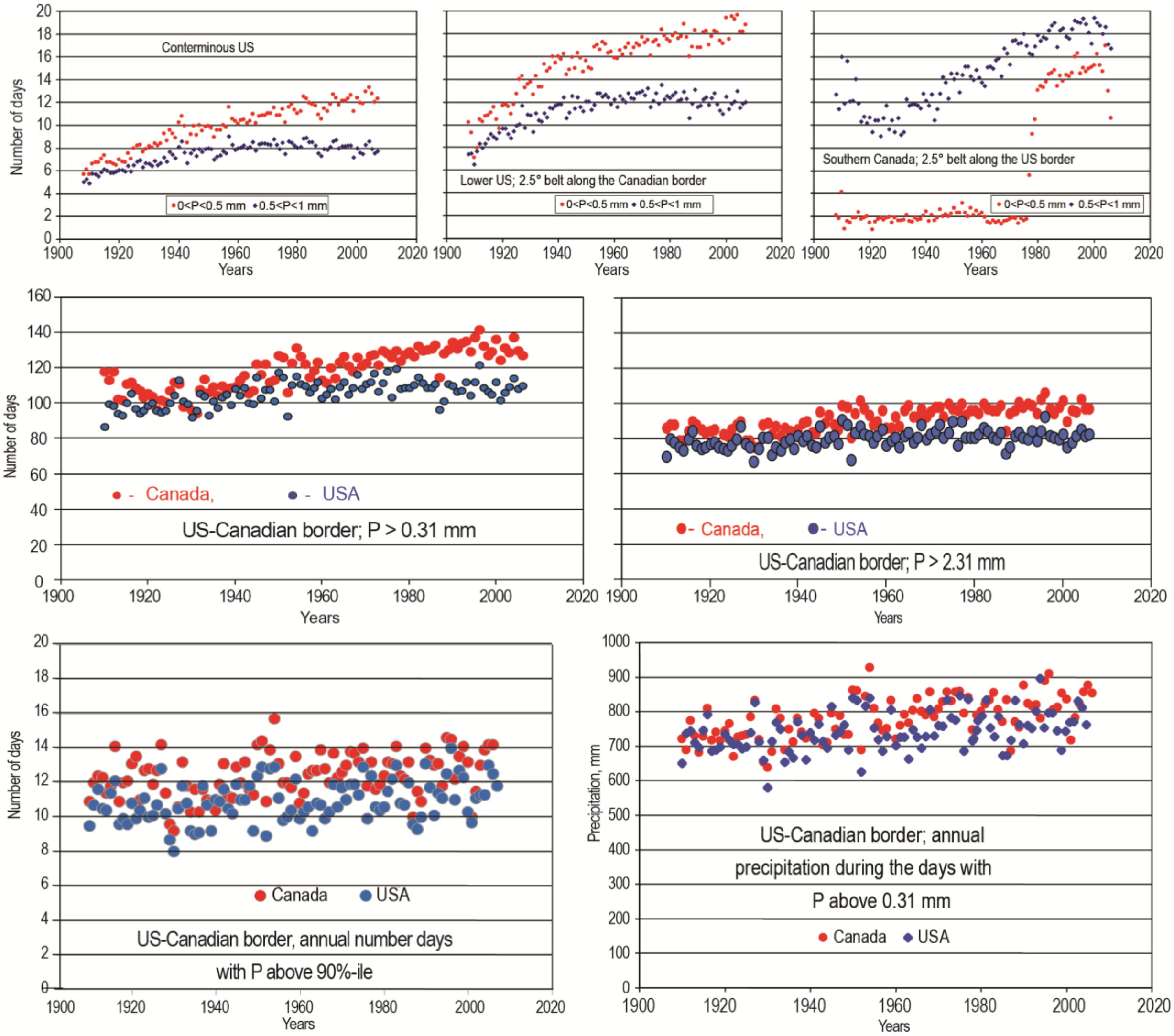


Figure 5.1.11. **Top panel**. Mean number of days with non-zero very light daily precipitation over the conterminous United States (left; Groisman and Knight 2007, 2008) and along the 2.5-degree latitudinal belt along the U.S. - Canadian border, U.S. (center) and Canadian (right) sides of the border. **Middle panels.** Annual number of days across the S Canadian border (±2.5° lat.) with precipitation (left) above 0.31 mm and (right) above 2.31 mm. Blue and red dots show the US and Canadian precipitation frequency respectively. Note the difference in trends, first of all, for Canada. **Low panels.** Annual number of days across the US Canadian border (±2.5° lat.) with heavy precipitation (upper 10%-ile; left) and precipitation totals for days with P above 0.31 mm (right). Blue and red dots show the US and Canadian precipitation frequency respectively.

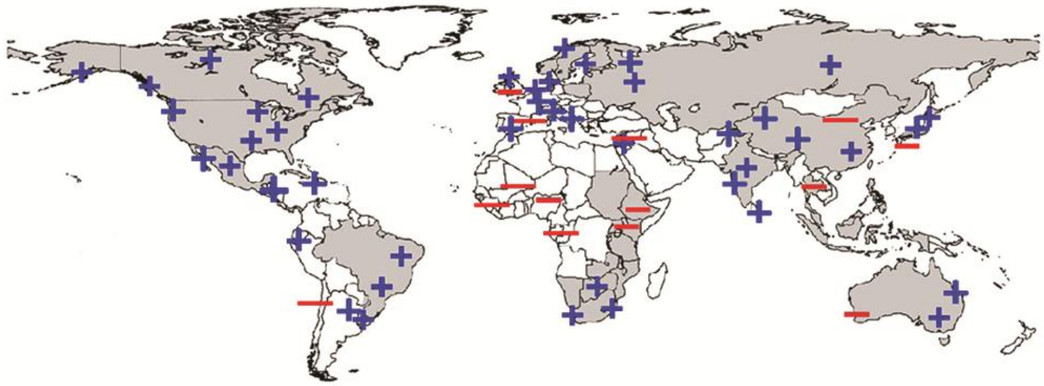


Figure 5.1.12. Regions where disproportionate changes in heavy and very heavy precipitation during the past decades were documented compared to the change in the annual and/or seasonal precipitation (Easterling et al. 2000, Groisman et al. 2005, substantially updated first in Trenberth, Jones et al. 2007 and for the present Chapter). 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.

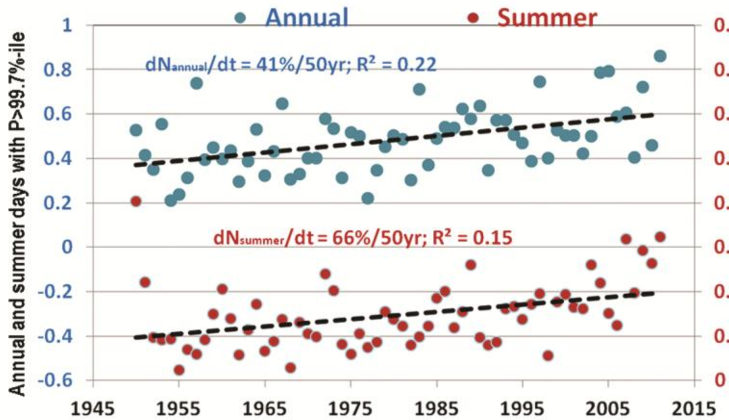


Figure 5.1.13. Frequency of very heavy (above the upper 0.3 percentile) annual (blue) and summer (dark red) daily precipitation events during the 1950-2011 period over Fennoscandia. All linear trends (shown by dashed lines) are statistically significant at the 0.01 level or above (updated time series from Groisman et al. 2005). Mean regional numbers were produced by the arithmetic averaging of the actual stations' numbers of days with very heavy precipitation within the 1ºx1º grid cells with the appropriate area-weights averaging of the grid cell values.

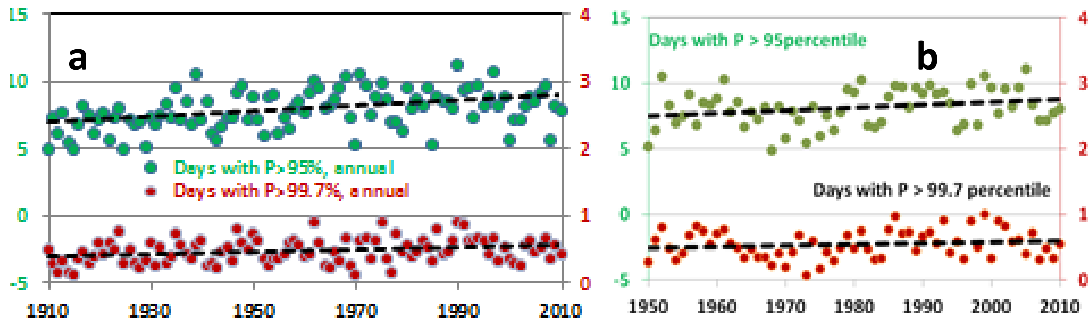


Figure 5.1.14. Heavy and very heavy annual precipitation variations and linear trends along the northwestern coast of North America (a) British Columbia south of 55°N and (b) Alaska south of 62°N. Statistical significance of linear trends is provided in Table 5.1.3. Mean regional numbers were produced by the arithmetic averaging of the actual stations' numbers of days with heavy and very heavy precipitation within the 1ºx1º grid cells with the appropriate area-weights averaging of the grid cell values.

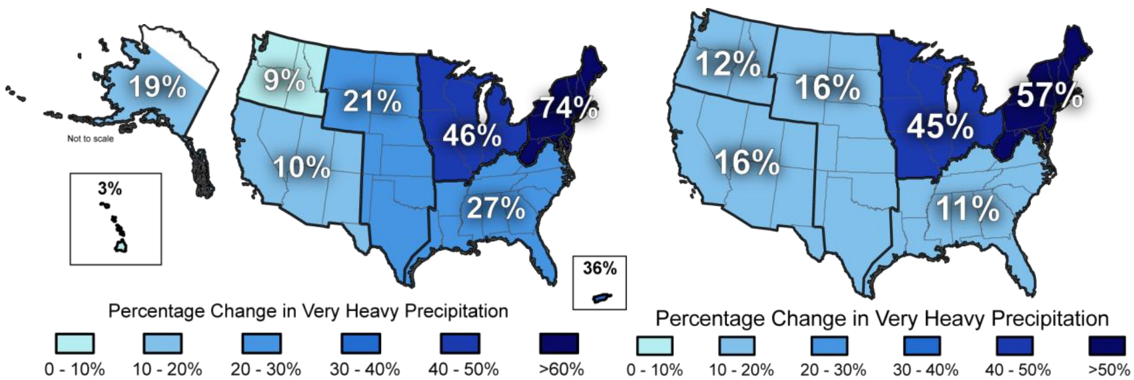


Figure 5.1.15. Observed increases in very heavy precipitation during the 1958-2010/11 (update of similar finding presented in USCCSP 2009). *Left*. Percent increases in the annual amount falling in very heavy rain events defined as the heaviest 1 percent of all daily events from 1958 to 2010 for each region of the United States. Changes in the Eastern half of the nation are statistically significant at the 0.05 or higher levels and over the Great Plains, at the 0.1 level. *Right*. Percent increases in the amount falling in very heavy rain events defined as the heaviest 1 percent of all daily events from 1958 to 2011 in the summer season for each region of CONUS. Changes over the north-central and north-eastern parts of the nation are statistically significant at the 0.01 and 0.05 levels respectively; all other trends are insignificant.

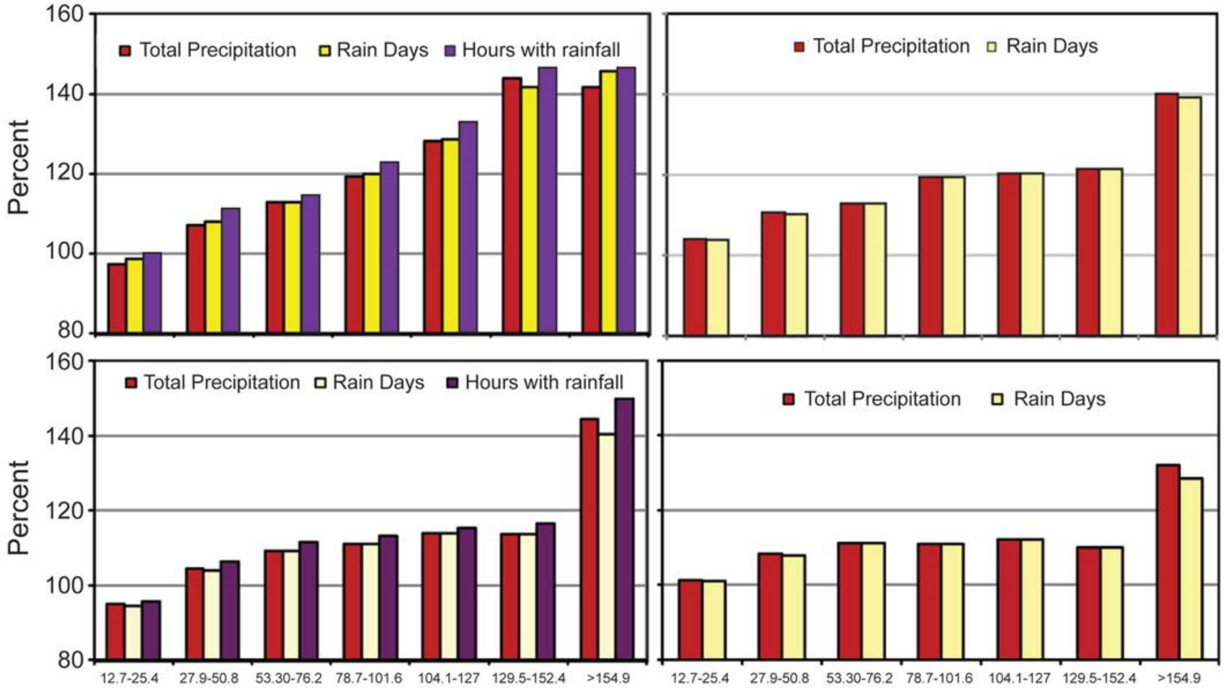


Figure 5.1.16. Comparison of intense precipitation days (upper line of plots) and multi-day intense precipitation events (lower plots) over the Central U.S. for 1979-2009 and 1948-1978 periods sorted by day/event intensities (in mm). Estimates of precipitation characteristics for these 31 year periods were averaged and their ratios (in percent per station) are shown for HPD (left) and COOP (right) networks.

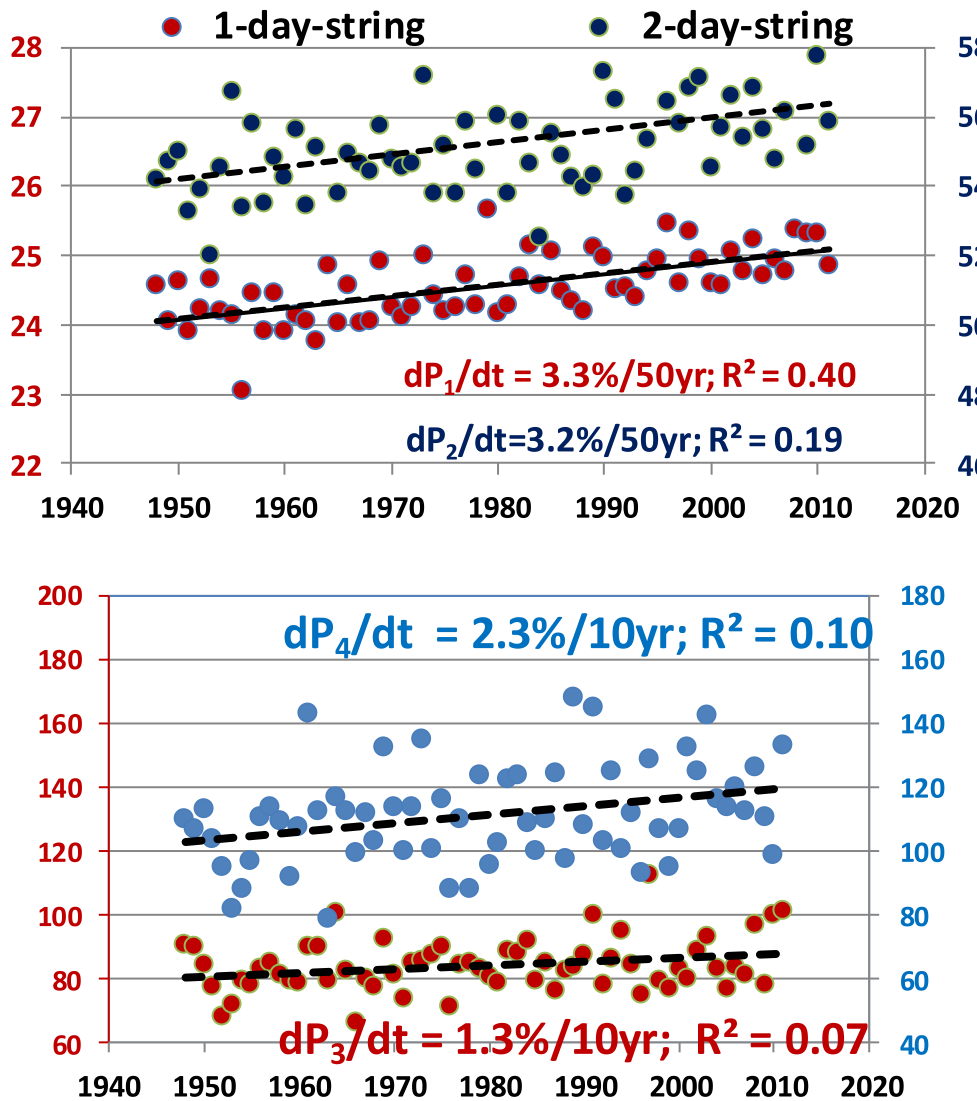


Figure 5.1.17. **Top panel.** Mean intense precipitation, mm, per event that comes with 1-day- and 2-day-long events over the contiguous U.S. The estimates are based upon all intense events above 12.7 mm at ~6,000 long-term U.S. cooperative stations for the 1948-2011 period. **Bottom panel**. The same but for 3-day- and 4-day-long events over the Midwestern U.S. (Archive of Groisman et al. 2012).

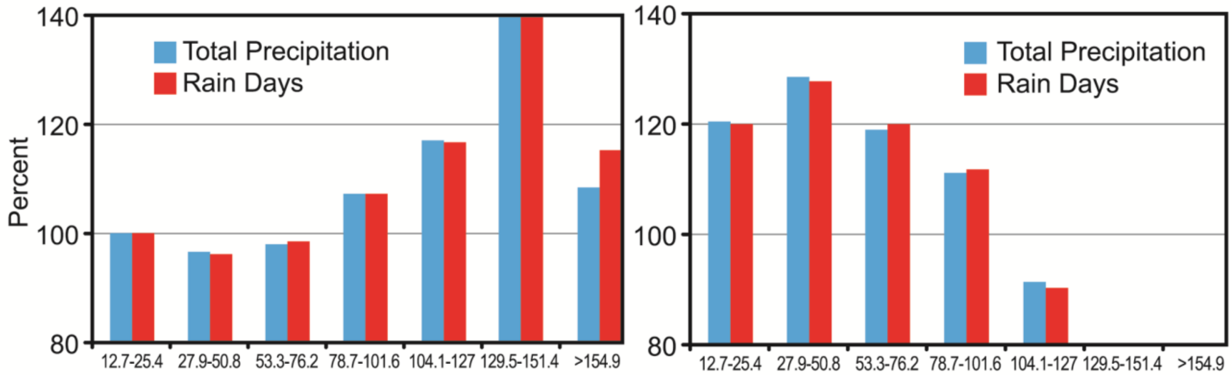


Figure 5.1.18 Same as Figure 5.1.16 but for daily precipitation events (COOP network) over the northwestern (Washington, Oregon, and Idaho; left) and southwestern (Four Corners; Utah, Colorado, Arizona, and New Mexico; right) United States.

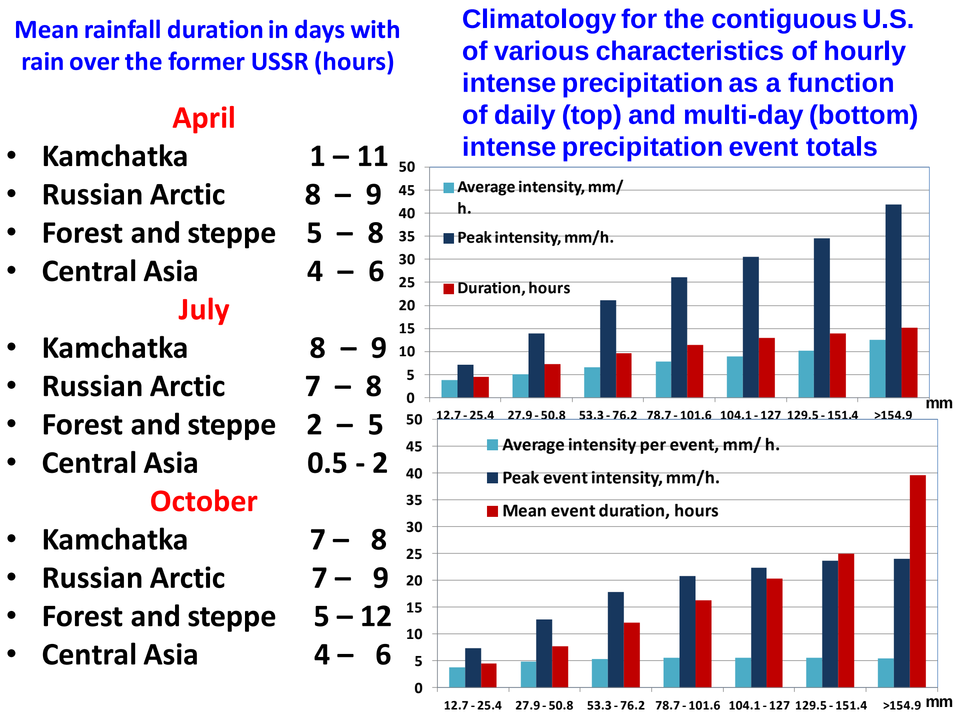


Figure 5.1.19. Precipitation duration in the extratropics estimated by recording gauges in Northern Eurasia (Lebedev 1964) and the United States (archive of Groisman et al. 2012). Only intense daily events (>12.7 mm) are considered for the contiguous U.S.

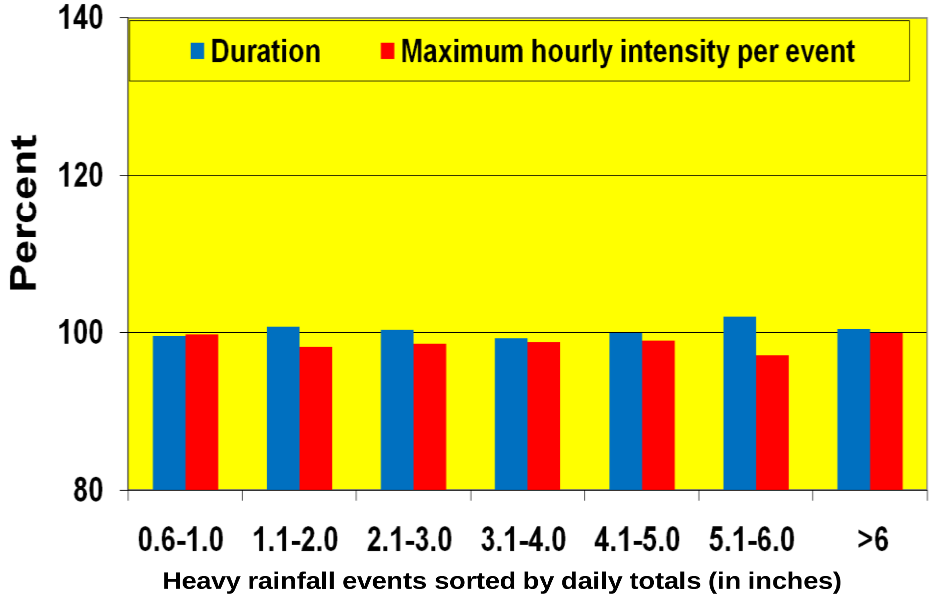


Figure 5.1.20. Comparison of heavy rainfall characteristics in the "warm" and "cold" Northern Hemisphere years in the eastern half of the contiguous U.S. (east of the Mississippi River). Data of 1,715 Hourly Precipitation (HPD) stations for the 1948-2007 period were used in this comparison. Warm and cold years rainfall records were scaled to the same number of stations available in both 30-year-long periods with the difference in the mean annual surface air temperature, ΔT_{NH}, equal to 0.54°C. Heavy daily rainfall events are sorted by the rainfall totals in the same manner as in Figures 5.1.2 and 5.1.16 but the x-axes is in inches.

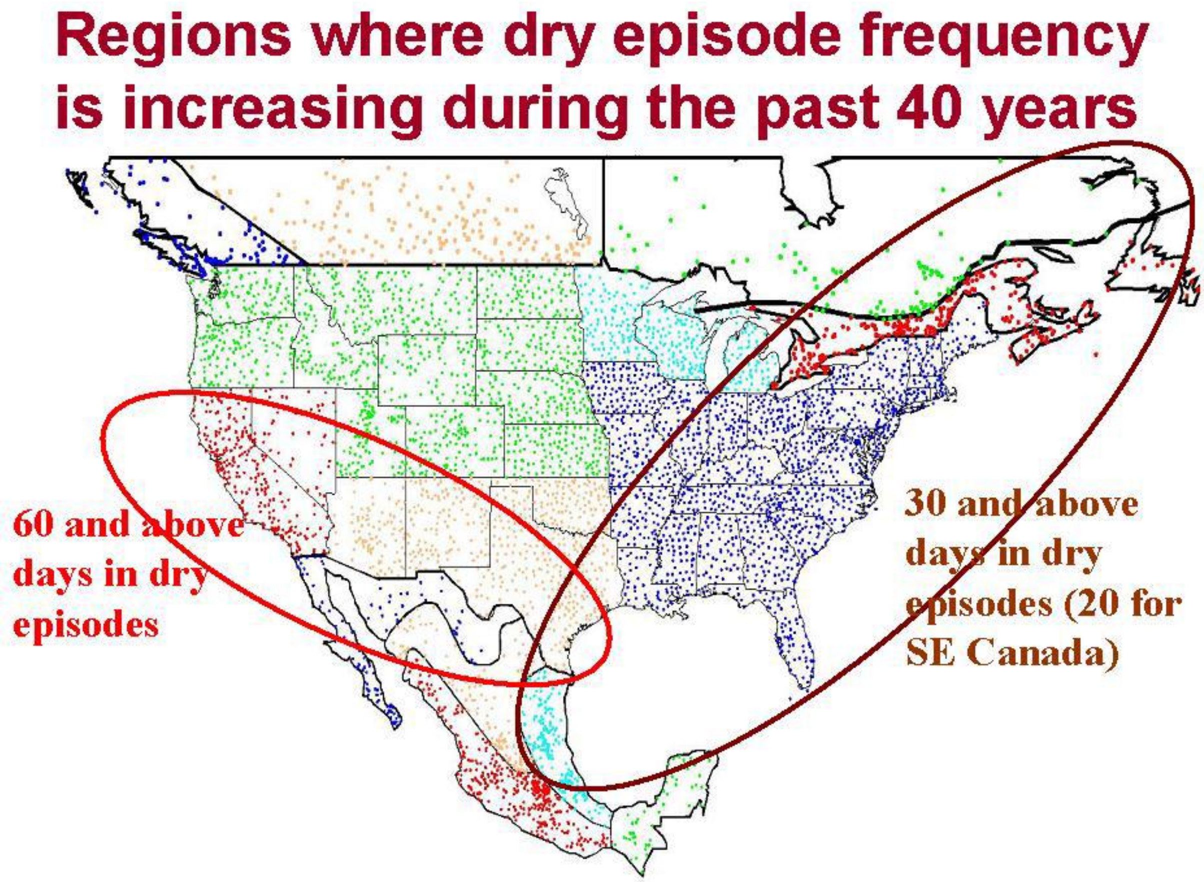


Figure 5.1.21. Schematic summary of statistically significant results showing the increase of prolonged dry day episodes across North America during the 1967-2006 period. Dots show the station locations with daily rainfall and temperature data used in the analysis and the dot colors (and solid lines) outline the regional boundaries within which the authors evaluated regional estimates of no-rain periods (Groisman and Knight 2007, 2008).

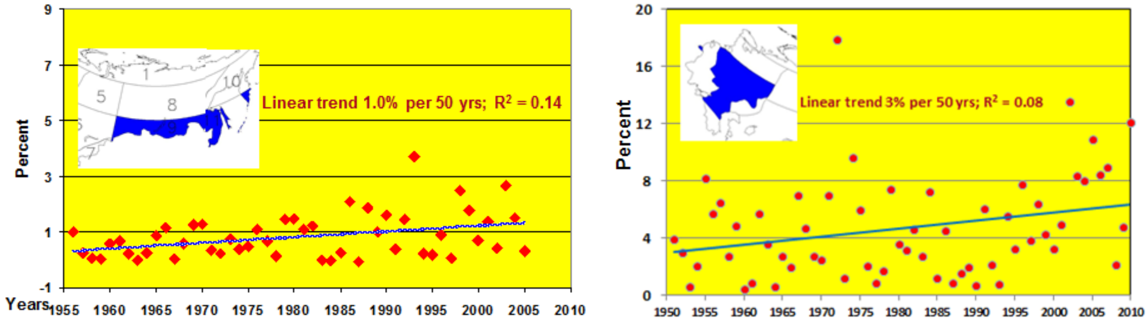


Figure 5.1.22. Dry episodes above 30 days during the warm season over (**left**) Asian Russia east of 85°E and south of 55°N and (**right**) European Russia south of 60°N. Both linear trends are statistically significant at the 0.05 level.

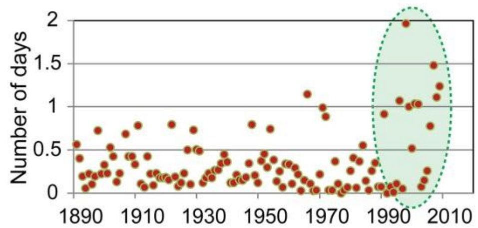
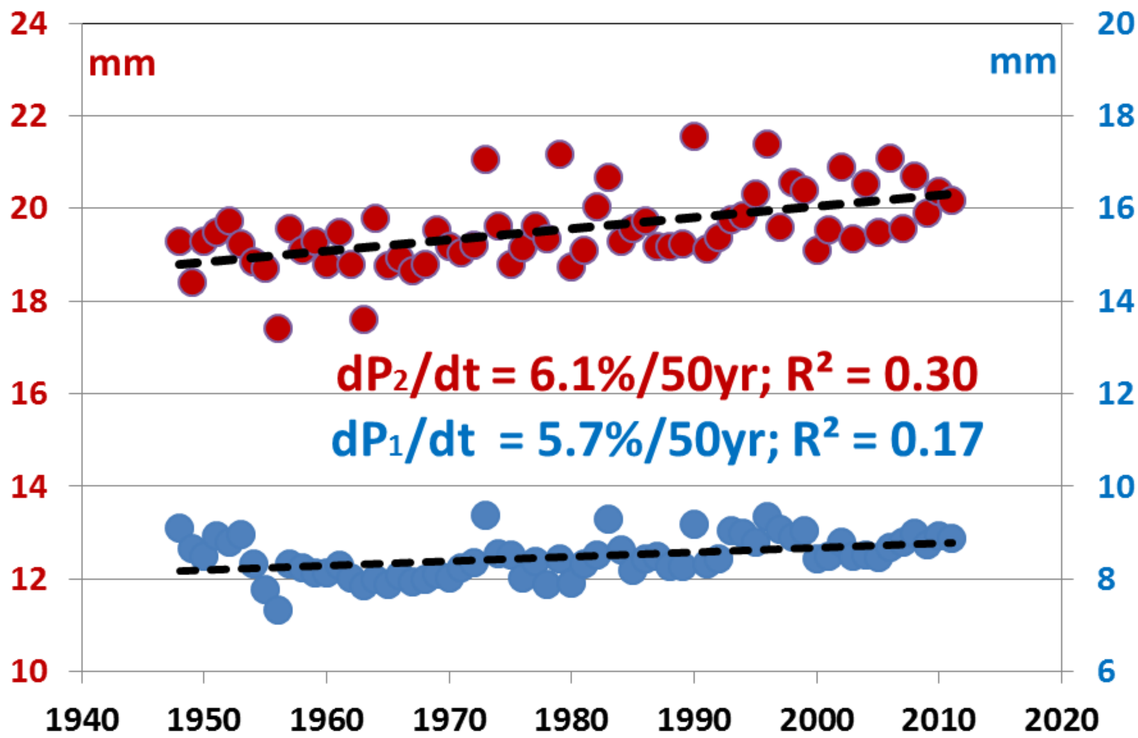


Figure 5.1.23. Number of days with "hot" nights (when minimum daily surface air temperatures remain above 23.9°C) area-averaged over ER south of 60°N during the 1891-2009 period. This number for 2010 exceeds 5. These days closely correlate with an increased mortality of unprotected population.



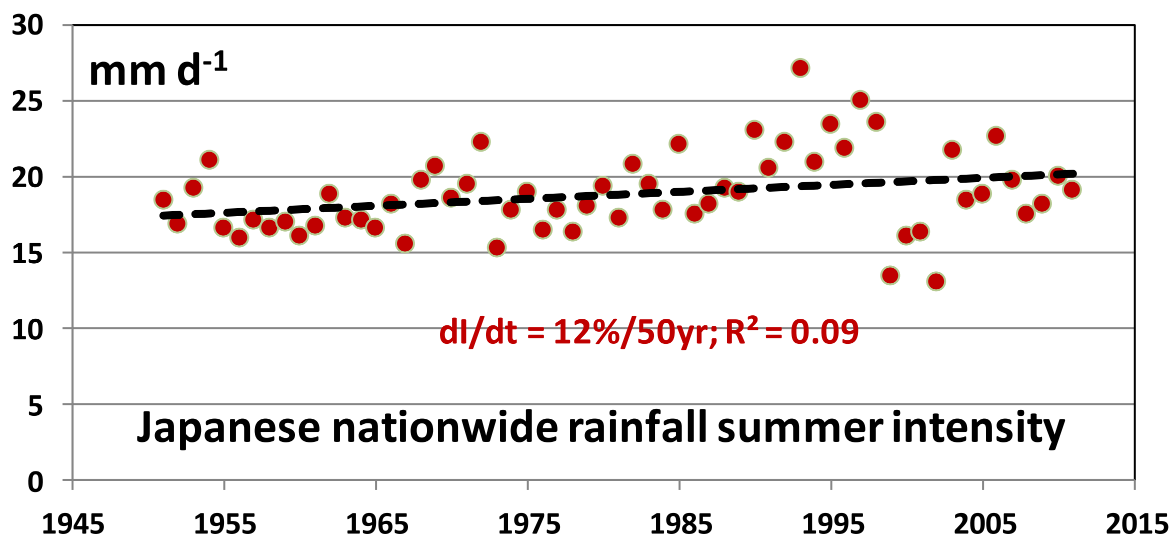


Figure 5.1.24. Top. Mean daily precipitation, mm, per event that comes with 1-day- and 2-day-long events over the contiguous U.S. The estimates of precipitation intensity in 1-day-long (P_1, mm day^{-1}) and two-day-long (P_2, mm (2 days)$^{-1}$) are based upon all precipitation events above 0.5 mm at ~6,000 long-term U.S. cooperative stations during the 1948-2011 period (Updated archive of Groisman et al. 2012). P_1 and P_2 were selected to be non-overlapping events (1-day events are not included in the 2-day events) and together contribute approximately 60% of nation precipitation totals. **Bottom.** Mean summer (JJA) rainfall intensity, mm d^{-1} over Japan. Estimates of the annual precipitation intensity over the country also show an increase (with the mean rate of 14%/50yr) but are not presented here due to our concerns about the instrumental homogeneity of the cold season precipitation measurements in this country after introduction of automation in early 1990s and thereafter.