OBSERVED VARIABILITY AND TRENDS IN EXTREME CLIMATE EVENTS: A BRIEF REVIEW

D.R. Easterling[1], J.L. Evans[2], P. Ya. Groisman[3], T.R. Karl[1], K.E. Kunkel[4], P. Ambenje[5]

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Contact Person: Dr. David R. Easterling: NOAA/National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801, USA; Ph. +1 828 271-4675; Fax: +1 828 271-4328; e-mail: deasterl@ncdc.noaa.gov

Abstract

Variations and trends in extreme climate events have only recently received much attention. Exponentially increasing economic losses, coupled with an increase in deaths due to these events, have focused attention on the possibility that these events are increasing in frequency. One of the major problems in examining the climate record for changes in extremes is a lack of high quality long-term data. In some areas of the world increases in extreme events are apparent, while in others there appears to be a decline. Based on this information increased ability to monitor and detect multi-decadal variations and trends is critical to begin to detect any observed changes and understand their origins.

[1] NOAA/National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801, USA
[2] Dept. of Meteorology, Pennsylvania State University, University Park, PA 16802 USA
[3] UCAR Project Scientist at National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801 USA
[4] Illinois State Water Survey, 2204 Griffiths Dr., Champaign, IL 61820 USA
[5] University of Nairobi, Nairobi, Kenya

Introduction.

Extreme weather and climate events have received increased attention in the last few years, due to the often large loss of human life and exponentially increasing costs associated with them (Changnon et al. 1999). In 1998 flooding and landslides due to Hurricane Mitch resulted in more than 10,000 deaths in Central America;, and in 1995 economic losses on the U.S. mainland due to hurricanes averaged $5 billion (normalized to 1995 levels) per year (Pielke and Landsea 1998). This increased attention raises the question as to whether extreme weather and climate events are truly increasing, whether this is only a perceived increase exacerbated by enhanced media coverage, or both (Karl and Easterling 1999). Ungar (1999) examined the possibility of enhanced media attention biasing the public perception that extreme weather events are increasing. Results indicated that in the U.S. there appears to be an increase in media coverage, but in other parts of the world no increase was evident.

There is little doubt that society as a whole has become more vulnerable to extreme weather (Kunkel et al. 1999b). Population and infrastructure continues to increase in areas that are vulnerable to extremes such as flooding, storm damage, and extreme heat or cold. Moreover, certain landscape use and societal infrastructure changes can often further increase vulnerability by, for example, creating more potential for catastrophic impacts from climate extremes, such as flooding and increased pollution with these events. In September, 1999 Hurricane Floyd, though not an overly powerful storm when it made landfall in eastern North Carolina, dumped copious amounts of precipitation which lead to major stream flooding, and in turn caused numerous deaths. In addition to the direct damage to infrastructure in the flooded areas, storm runoff also created a major pollution event due to flooding of sewage treatment facilities, farms resulting in the deaths and scattering of millions of farm animals, farm waste lagoons, and chemical and petroleum storage facilities with uncertain long-term consequences to fluvial and coastal ecosystems as yet unknown. In this case, the type of use of the watershed severely exacerbated the impacts of this event.

Climate Extremes and Data Issues.

There are a number of ways extreme climate events can be defined, such as extreme daily temperatures, extreme daily rainfall amounts, large areas experiencing unusually warm monthly temperatures, or even storm events such as hurricanes. Extreme events can also be defined by the impact an event has on society. That impact may involve excessive loss of life, excessive economic losses or be monetary, or both.

Lack of long-term climate data suitable for analysis of extremes is the single biggest obstacle to quantifying whether extreme events have changed over the 20^{th} century, either worldwide or on a more regional basis (Easterling et al. 1999). This includes high temporal and spatial resolution observations of temperature, precipitation, humidity, winds, and atmospheric pressure, for many parts of the world. For example, Figure 1 shows the areas of the world where analyses of heavy precipitation have been completed. For most countries the analysis period is only since WWII, but in four countries (Australia, USA, Norway, and South Africa) analyses began near the start of the 20^{th} century. However, changing cost recovery policies in different countries are hampering international data exchange (Karl and Easterling 1999). Furthermore, the daily data often are not in digital form. Indeed, even in the United States where large amounts of climate data are readily accessible, there is a large quantity of high temporal resolution data for the period prior to 1948 that are only now being digitized. If the data are available, issues of quality control, homogeneity, and completeness also must be considered since all can affect an analysis of extreme events (Easterling et al. 1999).

Given these questions, the extent to which we can document changes in extreme weather events, and the additional insights needed to perform more through analyses of these events in the observed record are of particular interest here. Specifically we review recent research onin extremes, focusing particularly on extremes where data have the potential to be robust enough to examine direct changes in these events over the 20th century.

Observed Trends.

It is useful to begin to examine trends in extreme events in the context of trends in more widely examined quantities such as average annual temperature. It is clear from the observed record that there has been an increase in the global mean temperature of about 0.6°C since the start of the 20th century (Nicholls et al., 1996), and that this increase is associated with a stronger warming in daily minimum temperatures than maximums (Easterling et al. 1997). Global precipitation has also increased over the same period (Nicholls et al. 1996). Given these increases, it is expected that there would also be increases in what are now considered extreme events (Mearns et al. 1984). Therefore, if there are indeed identifiable trends in extreme climatic events it would add to the body of evidence that there is a discernable human affect on the climate.

Temperature Extremes.

Relatively little work has been completed related to changes in high frequency extreme temperature events as shown in Table 1. This includes heat waves, cold waves, and number of days exceeding various temperature thresholds. Two studies focused on the Northeastern U.S. support the notion that changes in the number of days exceeding thresholds have occurred. Cooter and LeDuc (1995) show that the start of the frost-free season in the Northeastern U.S. occurs 11 days earlier now than in the 1950s. In an analysis of 22 stations in the Northeastern U.S. for the 1948-1993 period, DeGaetano (1995) found significant trends to fewer extreme cold days, but also trends to fewer warm maximum temperatures as well. More recently, Easterling (1999) examined trends in the number of days in the U.S. exceeding thresholds of 0°C, 32.2°C (90°F), and thresholds derived using non-parametric statistics (percentiles). Trends indicate that for the 1910-1998 period, there has been a slight decrease in the number of days below freezing over the entire U.S. However there is much regional variation in the trends. Trends in the number of days with the maximum temperature over both 32.2°C and the 90th percentile threshold are dominated by large anomalies, partially due to the very dry land surface conditions during the droughts of the 1930s and 1950s. Overall there is a slight downward trend in the number of these extremes despite an overall warming in the mean temperature, but with cooling in the Southeastern U.S. (Karl et al. 1996). In both Australia and New Zealand, the frequency of days below freezing decreased coincident with warming in daily minimum temperatures (Plummer et al. 1999). In New Zealand this decrease and a slight increase in the number of days exceeding 30°C appear to be in response to changes in atmospheric circulation in the region; these changes show a good relationship with warming in mean annual temperature (Plummer et al. 1999). In Northern and Central Europe, Heino et al. (1999) found evidence of a decreasing numbers of frost days since the 1930s which appears to be associated with strong increases in winter minimum temperatures.

Apparent temperature, which combines temperature and humidity effects on the human body, is another important measure, particularly for human health. Gaffen and Ross (1998) show regional summertime increases in days exceeding the 85th percentile threshold value for apparent minimum, mean, and maximum temperature in the U.S. This result would appear to be in contrast to trends found by Easterling (1999) for the 1910-1998 period. However the period used by Gaffen and Ross (1998) was 1948-1995, which would exclude the effects of the 1930s droughts on extreme high temperatures. Also, the trends for maximum apparent temperature in Gaffen and Ross (1998) are statistically significant only for the western U.S. Lastly, the network of observing stations Gaffen and Ross (1998) use are mainly airport sites, which likely have at least some urban warming influence. The network used in Easterling (1999) is composed mainly of more rural sites contained in the U.S. Historical Climatology Network (Easterling, et al. 1996).

Short-duration episodes of extreme heat or cold are often responsible for the major impacts on health as evidenced by the 1995 heat wave in the Midwestern U.S. that resulted in hundreds of fatalities in the Chicago area (Changnon et al. 1996). Although this heat wave was one of the worst short-duration events of the 20th Century (Kunkel et al. 1996), an analysis of multi-day extreme heat and cold episodes where the temperature exceeds the 10-year return period do not show any overall trend for the period of 1931-1997 (Kunkel et al. 1999b). The most notable feature of the temporal distribution of these very extreme heat waves is the high frequency in the 1930s compared to the rest of the record. Again, this would appear at odds with the results of Gaffen and Ross (1998); however this points out the difficulty of comparing results using different periods, and different ways of defining an extreme event. Since Gaffen and Ross use apparent temperature, which includes humidity, part of their increase is likely due to increases in water vapor and indeed Ross and Elliot (1996) show evidence of precipitable water vapor increases over North America for the 1973-1993 period.

Absolute daily extremes of both maximum and minimum temperature by month and annually for the U.S. and former Soviet Union show little or no trend for the maximum temperatures, but generally show strong increases for the minimum temperature for the 1951-1989 period (Karl et al. 1991). Furthermore, in China there has been a slight decrease in the 1-day extreme maximum temperature during every season but spring, but the extreme minimum temperature exhibited a strong increasing trend in each season (Zhai et al. 1999).

One thing that is clear in Table 1 is that for every country where the number of frost days has been examined they are becoming fewer in number. This is consistent with the warming in average minimum temperature found for each country (Easterling et al. 1997). However, results for other temperature extremes are much less consistent, particularly warm maximum temperature extremes. Again, this is broadly consistent with trends found for average maximum temperatures which are less consistent across the countries analyzed by Easterling et al. (1997).

Extreme Precipitation.

Trends in one-day and multi-day heavy precipitation events in the United States and other countries show a tendency to more days with heavy 24-hour precipitation totals (Karl and Knight 1998). The number of days annually exceeding 50.8 mm (2 inches) of precipitation has been increasing in the U.S. (Karl et al. 1996). Also, the frequency of 1 to 7-day precipitation totals exceeding station-specific thresholds for 1 in 1 year and 1 in 5 year recurrences as well as the upper 5 percentiles have been increasing (Karl and Knight 1998, Kunkel et al. 1999a). Increases are largest for the Southwest, Midwest, and Great Lakes regions of the U.S., and increases in extreme events are responsible for a disproportionate share of the observed increases in total annual precipitation (Groisman 1999).

The tendency in most countries that have experienced a significant increase or decrease in monthly or seasonal precipitation has been for this change to be directly related to a change of the same sign in the amount of precipitation falling during the heavy and extreme precipitation events. Table 2 and Figure 2 show linear trends in total and heavy precipitation above various thresholds for a number of countries. Over most of the areas discussed, there has been changes of the same sign (increasing or decreasing) in both the seasonal totals and the frequency of 1-day heavy precipitation events, but in either case the heavy precipitation changes were always disproportionately large. Furthermore, in some cases there was no increase in the seasonal total but there was still an increase in the frequency of 1-day heavy precipitation events, as found in Japan (cf., Iwashima and Yamamoto 1993).

There have been a few analyses of heavy precipitation events for other parts of the world; however for most areas analyzed results are consistent with those discussed above. For example, in Australia much of the country has experienced increases in heavy precipitation events in all parts of the year, except in Southwestern Australia where there has been a decrease in both rain days and heavy events (Suppiah and Hennessy 1998). In the United Kingdom increases in heavy wintertime events and decreases in heavy summertime events have been found (Osborn et al. 1999), and in the Sahel region of Nigeria there has been a decrease in the heaviest daily precipitation amounts, coincident with an overall decrease in annual rainfall (Tarhule and Woo 1998). This pattern is apparent throughout all Sudano-Sahel Zone including Abissinian Plateau. These changes are consistent with the decrease in heavy precipitation over this region shown in Table 2. On the other hand, Akinremi et al. (1999) found that, although the Canadian prairie has experienced increased annual rainfall over the last 40 years, but this increase appears mainly due to an increase in the number of lighter (< 5 mm) daily rainfall totals.

Drought and Wet Periods.

An important aspect of climate extremes is related to excessive drought or wet periods. A recent analysis by Dai et al., (1998) shows increases in the overall areas of the world affected by either drought and excessive wetness. Examination of drought over the 20^{th} century in the U.S. shows that there is considerable variability, with the droughts of the 1930s and 1950s dominating any long-term trend (Karl et al. 1996, Kunkel et al. 1999b). Recent investigation of longer-term variability over the past 2000 years using paleoclimatic data indicates that large droughts, such as the 1930s droughts, can be expected to occur once or twice a century in the Central United States, and that multi-decadal mega-droughts extending over larger areas occur every few hundred years (Woodhouse and Overpeck 1998).

Although there appear to be no long-term trends in drought, the area of the U.S. experiencing excessive wetness appears to be increasing, particularly since the 1970s (Karl et al. 1996). This is consistent with long-term increases in annual precipitation, and increases in heavy precipitation events. Analysis of drought for other regions of the world shows some trend to more drought. Hungary shows an increasing trend in droughts, with a decrease in wet spells (Szinell 1998), and over China, a long-term decrease in mean precipitation (Ye et al. 1996) has been accompanied by an increase in the area of droughts and a decrease in the area with excessive precipitation (Nicholls et al. 1996).

Tropical Storms.

Overall, occurrences of Atlantic hurricanes do not show a statistically significant long-term trend over the 20th century. However Landsea, et al. (1999) found a statistically significant decrease in intense hurricanes, those that cause the most damage. From 1944 to the mid-1990s the number of intense and landfalling Atlantic hurricanes has declined (Landsea 1993, Landsea 1996). Furthermore, large variations of hurricane activity on interdecadal timescales have been observed in this century (Gray et al. 1997). Since the majority of coastal settlement occurred in a period of relatively low hurricane landfall frequency, the potential societal impacts of hurricane landfall in more active decades have yet to be realized (Pielke and Landsea 1998).

Recent work has documented the contribution of hurricanes to very extreme rainfall events (the individual event results in double the monthly rainfall being measured in that month) in the mid-Atlantic and New England regions of the USA (Evans and Hart 1999). For the 67 year period studied, eastern Massachusetts and much of the Appalachians experience such extreme rainfall events on average every 5-6 years, and the return period drops to 2-4 years when hurricane rainfall contributions result in monthly rainfall anomalies of 150% above average.

In the North Pacific basin a positive trend has been observed in both in tropical storm activity and typhoons since the mid 1970s (Chan and Shi 1996). Prior to the mid-1970s, tropical storm activity in the western North Pacific region had been dropping, demonstrating a nonlinear longer-term variation in tropical storm frequency in this most active region of the globe. Since 1969 a strong downward trend in tropical storm frequency has been observed in the Australian region, south of the equator, (105 E-160 E) which has been largely attributed to variations in the El Nino/Southern Oscillation (Nicholls et al. 1998).

Indices of Climate Extremes.

Since climate extremes can be defined as large areas experiencing unusual climate values over longer periods of time (e.g. large areas experiencing severe drought), one way to investigate trends in climate extremes over time is to develop indices that combine a number of these types of measures. Karl, et al. (1996) introduced an index for the U.S. that is composed of percent area with extremes in maximum and minimum temperature (both warm and cold), the Palmer Drought Severity Index (for both dry and wet periods), extreme precipitation, and the number of days with precipitation. This Climate Extremes Index shows large decadal fluctuations over the 20th century. However since the late 1970's the Index has remained high suggesting that the U.S. is experiencing more of these types of extremes. A similar index has been proposed for Canada that also includes parameters important to high latitude climates, such as extreme snow accumulation and wind (Easterling et al. 1999).

Summary and Discussion.

The preceding review has raised a number of important questions regarding potential changes in extreme events. For many areas analyzed there have been significant changes in short-term extreme events, such as temperature and precipitation. However, for other events such as land-falling Atlantic hurricanes an increase perceived by the general public has not occurred, and in fact the occurrence of certain rare events, such as intense hurricanes has declined. More integrative approaches, such as the development of climate extremes indices that include information on large-area, longer-term extremes show promise in analyzing the question of whether the climate in general has become more variable or extreme. This is particularly true for areas of the world where higher temporal resolution data are not available. However, indices have only been developed for the United States, and are in development for a number of other areas such as Canada and Europe.

As far as attribution of trends, both in mean values and extreme events, one of the most critical issues relates to the hypothesis that with greenhouse gas-enhanced climate change the hydrologic cycle should intensify. There is some evidence that this is occurring, however most observational studies are based on relatively short time periods and results cannot be considered unequivocal evidence of climate change. Such evidence includes the observed increase in annual precipitation amounts, particularly in higher latitudes, regional increases in heavy precipitation amounts, and observed increases in atmospheric humidity in North America (Ross and Elliot 1996), China (Zhai and Eskridge 1997) and soil moisture in the former Soviet Union (Georgievsky et al. 1998). Trenberth (1999) proposes a conceptual model showing the effect of increased greenhouse gases on the hydrologic cycle and other factors affecting many climate extremes. Within this model increased radiative forcing increases surface heating and latent heating resulting in both increased air temperature and evaporation. This would lead to increased atmospheric water vapor content, increased precipitation rates, and enhanced storm intensity.

One of the biggest problems in performing analyses of extreme climate events for most of the globe is a lack of access to high-quality, long-term climate data with the time resolution appropriate for analyzing extreme events. International data exchange is becoming increasingly difficult as countries develop cost recovery programs for access to climate data. Furthermore, much high temporal resolution data remains undigitized throughout the world. More support for programs such as the World Meteorological Organization=s Data Rescue Project is needed. Homogeneity of data is also a problem, particularly in examining extremes as in days exceeding a specific threshold. Observations of extremes such as thunderstorms and tornadoes often have biases due to such factors as increased population density and for that reason have not been considered here. For example, the increase in tornado observations in the United States in this century is likely due as much to the fact that more people live in tornado prone areas and are able to report tornado occurrences that otherwise would have gone unreported, as any real increase. To address these types of homogeneity and biasing problems, particularly for randomly occurring events like thunderstorms, one approach is to use a surrogate for extreme weather such as examining long-term variability and trends in atmospheric conditions known to be conducive to severe weather. Lastly, it is critical that monitoring efforts, such as the Global Climate Observing System (GCOS), receive enhanced support. Without such efforts our ability to detect long-term variability and trends in extreme climate events will remain hampered.

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Table 1: Summary of analyses of temperature extremes around the world.

Country	Frost Days	Warm Minimum Temperatures	Warm Maximum Temperatures	Cold Waves	Heat Waves
Australia	fewer		up		
China	fewer	up	down	fewer	
C. Europe	fewer				
N. Europe	fewer				
New Zealand	fewer		up		
U.S.	fewer	up	no trend	no trend	no trend

Table 2. Regions/seasons/periods where the linear trends of the number of days with heavy precipitation are amplified relative to changes in mean precipitation totals and frequency. Usually the season with maximum precipitation totals has been selected. Asterisk indicates a statistically significant difference from zero at the 0.05 significance level. In four regions (marked by **), we found a statistically significant increase in heavy precipitation, while mean precipitation total did not change (or even decreased) and the frequency of precipitation events has decreased during the same period. For Asian part of Russia this unusual pattern of changes has been attributed to the intensification of summer convective processes (Sun and Groisman 1999).

Country	Period	Threshold used to define "heavy" rain, mm	Season	Average number of days with heavy rain	Linear trend, %/10years
Eastern two-thirds of the contiguous USA	1910-96	50.8	JJA	0.6	1.7*
European part of the former USSR	1936-94	20	JJA	1.8	3.9*
Asian part of Russia**	1936-94	20	JJA	2.3	1.9*
Southern Canada	1944-95	20	JJA	2.9	1.9*
Coastal regions of New S. Wales and Victoria, Australia	1900-96	50.8	DJF	0.4	4.6*
Norway	1901-96	25.4	JJA	2.0	1.9
Southern Japan	1951-89	100	JJA	1.0	-6.1
Northern Japan**	1951-89	100	JJA	0.3	3.4*
Northeastern China	1951-98	50	JJA	1.0	-1.8
Southeastern China	1951-98	100	JJA	0.5	2.2
Ethiopia & Eritrea	1951-87	25.4	JJA	5.5	-11.6*
Equatorial East Africa	1950-97	50.8	MAM	1.1	-11.2*
S-W. South Africa	1926-97	25.4	JJA	0.7	5.5*
Natal, South Africa**	1901-97	50.8	DJF	0.6	4.1*
Brazil, Nord-Este**	1935-83	50.8	MAM	1.0	3.6
		100	MAM	0.1	16.1*
Thailand	1951-85	50.8	SON	2.2	-8.4*
		100	SON	0.4	-20.9*

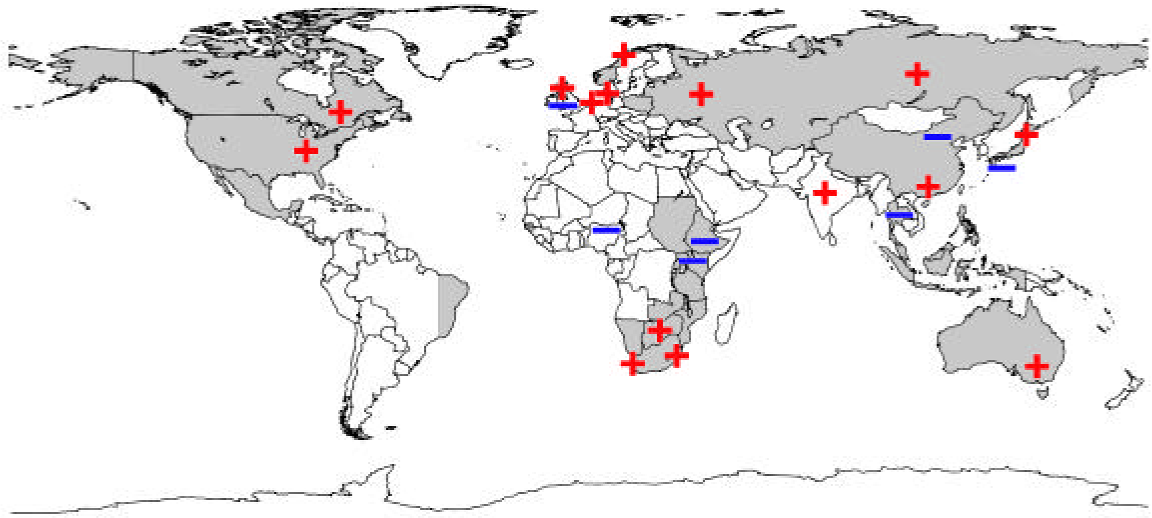

Figure 1. Regions for which the large sets of daily precipitation time series are available for analyses of precipitation extremes. Signs (pluses and minuses) indicate regions where significant changes in heavy precipitation have occurred during the past decades. Lightly shaded regions are those used in the summary shown in Table 1. Only for four countries (Australia, the United States, Norway, and South Africa) we were able to assess the century-long trends in daily precipitation. For other countries only the post-WWII period was analyzed.

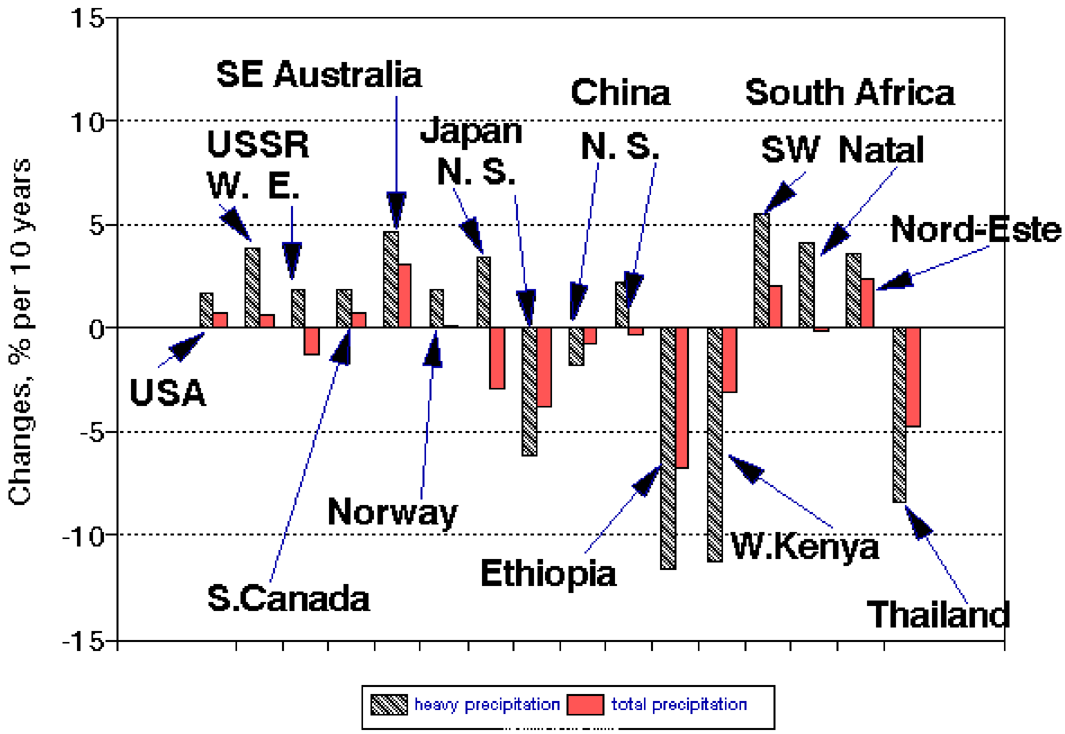

Figure 2. Linear trends in total seasonal precipitation and frequency of heavy precipitation events. Periods of record, seasons, and thresholds used to define heavy precipitation are shown in Table 2.