CLIMATE EXTREMES: SELECTED REVIEW AND FUTURE RESEARCH DIRECTIONS

THOMAS R. KARL and DAVID R. EASTERLING

NOAA/NESDIS/National Climatic Data Center, Asheville, NC, USA

Abstract. Trends and multi-decadal variations of weather and climate extremes have only recently received attention from the climate community. Interest has stemmed from exponentially increasing economic losses related to climate and weather extremes, and apparent increases in deaths attributed to these events, suggesting that key decision makers need a better understanding of the potential uses of climate information. The need for data on climate extremes in disaster mitigation activities such as the International Decade for Natural Disaster Reduction also has provided another motivation for focus in this area.

The losses cited above raise questions as to whether extreme weather events are actually increasing in frequency, whether society as a whole is becoming more vulnerable to extreme weather events, whether public perception has been unduly influenced by enhanced media attention, or some combination. Given these questions, of particular interest here is the extent to which we can document changes in climate and weather extremes. Attribution of ongoing trends to specific climate forcings, such as anthropogenic effects or other factors related to natural climate variability are still equivocal.

For some areas and variables increases in the frequency of extreme events are apparent, while in other areas there are suggestions of declines in these events. A review of this information suggests that further understanding of the cause(s) of the apparent changes in climate and weather extremes is strongly dependent upon progress in our ability to monitor and detect these multi-decadal trends. Based on these analyses we show that this will likely require increased attention in the following areas: 1) The development of more effective international data exchange for high resolution historical climate and weather records, 2) Increased emphasis on rescuing data with appropriate resolution from deteriorating manuscripts and other non-electronic media, 3) A greater emphasis on removing inhomogeneities[1] in the instrumental record and ongoing weather monitoring programs (that provide much of our information about changes and variations of weather and climate extremes), 4) More effective use of space-based measurements and reanalysis products derived from models, 5) More robust monitoring of local extreme weather events such as tornadoes, hail, lightning, and wind, and 6) More effective means to integrate and communicate information about what we know and do not know about changes in climate extremes. Progress in each of these areas is reviewed in context with outstanding remaining challenges, and the benefits that can be expected if we meet these requirements.

[1]Inhomogeneities are defined as changes and variations in the record that are non-climatic or are not representative of the time and space scales of interest, e.g., urban heat island effects are climate-related, but are not the scales of interest for global temperature change analyses.

Climatic Change **42**: 309–325, 1999.

1. Introduction

Each year extreme climate and weather events take tens of thousands lives, cause untold human hardship, and result in enormous economic losses. Since the late 1980's the insurance and re-insurance industry has pointed out an exponential increase in economic losses due to these events (Munich Re, 1996). In many countries the general public has also become concerned as press reports, first-hand experience, and anecdotal information all appear to suggest an increase in the frequency and severity of these events. Over the globe, economic losses have continued to increase during the 1990s, and although the number of disaster- related deaths has increased over the past 25 years (IFRCRCS 1997), the relative increase in weather-related deaths has not been as dramatic as the rapid increase in economic losses. For example, the enormous loss of life from the 1991 floods in Bangladesh, where an estimated 140,000 deaths occurred, was still considerably fewer than the 300,000 during the 1970 catastrophic floods. It is quite likely that improvements in communications and warning systems have played an important role in moving people out of harms way. Human infrastructure however, is not so mobile. The losses cited above raise questions as to whether extreme weather events are actually increasing in frequency, whether society as a whole is becoming more vulnerable to extreme weather events, whether public perception has been unduly influenced by enhanced media attention, or some combination. Given these questions, of particular interest here is the extent to which we can document changes in climate and weather extremes. There is little doubt that our vulnerability to extreme events is increasing as society continues to inhabit and develop vulnerable areas such as coastal margins and floodplains, and existing populations in these types of areas increase. Although there is some controversy as to whether urban areas are overly vulnerable to natural disasters (e.g. see Mitchell 1990 and Knovitz 1990), by nature of the fact that cities are areas of high population concentration with complicated interdependent infrastructure, there is little doubt that they are vulnerable to exceptional extreme weather events such as hurricanes, heavy flooding, or extreme temperature events. Moreover, changes in the natural landscape associated with mans infrastructure, (roads, parking lots, buildings, reservoirs, dams, alterations in streamflow, sewage and storm water routing runoff, etc.) can often contribute to major catastrophes during extreme rainfall events and flooding situations. The United Nations estimates that nearly half of the world's population lives in cities, up from 30% in 1950, and that by 2025, 60% of the world's population is expected to reside in urban areas.

In light of these socio-economic trends there are four fundamental issues related to variations and changes of climate extremes that are reviewed in this paper. This includes:

Can we detect any change in climate and weather extremes?

- Are these changes unusual in light of natural climate variability?

- Is there any evidence to link observed changes in extremes to anthropogenic effects?
- What priorities are needed to reduce uncertainties?

2. Observed Trends

The concern over potential impacts of climate change by various parts of society has been heightened by increases in weather related impacts that have occurred in recent years. Understanding potential climate change both in terms of trends, and changes in extreme events is critically important for a wide range of policy decisions (Pielke and Landsea 1998). Therefore, it is useful here to first examine observed trends in various parts of the climate that may have an impact, either directly or indirectly, on society. Furthermore, it should be made clear that a trend in one individual variable, such as the annual global temperature, does not necessarily confirm that climate change is occurring. However, it is the continued documentation of trends and changes in a number of key variables that adds to the body of evidence that there is a discerable anthropogenic impact on the climate. In the following sections we examine trends in various aspects of temperature, precipitation and storms, particularly as they relate to climate extremes. Due to a shortage of available data and subsequent analyses there currently is not strong evidence that on a global basis extreme weather events are increasing in severity or frequency. However, in some regions where data are available to examine these types of events there is clear evidence of changes in some extremes and overall climate variability (IPCC 1996). Lastly, it is becoming increasingly evident that human society is going to have to learn to live with whatever climate is produced by a substantial increase in CO_2. Although there is still debate, it is possible that the earth may see a doubling or even a tripling of atmospheric CO_2 sometime around the turn of the next century (Schneider 1998). If this is the case, then continued documentation of climate trends, particularly in terms of climate extremes, will be critical for decision makers in the future as they deal with environmental changes and their impacts.

2.1. TEMPERATURE

There is now clear evidence for an observed increase in global average temperatures of about 0.5°C since the start of the 20th century (IPCC, 1996). It is not as well appreciated however, that on regional scales, especially over land, the observed rates of temperature change are often several times larger. Clearly, if there are large changes in the mean, changes in the extremes of temperature are also likely (IPCC 1996). A recent analysis of 50% of the global landmass by Easterling et al. (1997) shows that indeed, the mean daily maximum and minimum temperatures are both increasing, but the rate of increase of the minimum temperature for the 1950-1993 period is more than twice the increase of the maximum (1.8°C/100 years versus 0.8°C/100 years). The increase in the mean minimum temperature has been demonstrated to have affected the length of the frost free period, which has potential impacts for a number sectors such as agriculture (growing season length and pest control) or power generation and consumption. For example, Cooter and LeDuc (1995) report that in the northeastern USA over the 1950-1994 period the frost-free period begins about 11 days earlier in the 1990's compared to the 1950's, and Easterling (1998) has shown that the northern Great Plains, western and northwestern USA have experienced a significant decrease in the number of days below freezing for the 1910-1997 period. Evidence for a significant reduction in the number of Twentieth Century frost-days in many portions of Australia has been documented in several reports, e.g., Plummer et al, (1999); Karl et al., (1997). Salinger (1997) also reports a decrease in the number of frost days over much of New Zealand during the Twentieth Century.

In Australia, the increase in the annual mean minimum temperature is quite consistent with reduced frost days, but in the Northeast USA the change in the mean minimum temperature is quite small relative to the change in the spring frost date. This is not an unusual circumstance, and points to the danger of broad generalizations based on changes in the mean. For example, the work of Rogers and Rohli (1991) and Downton and Miller (1993) document an increase in the frequency of major freezes affecting Florida during the late 1970s and 1980s, yet the mean minimum winter temperature during that time was comparable to values during the 1950s and early 1960s. Nonetheless, in New Zealand, Salinger (1997) reports a good relationship between the mean annual temperature and the number of days below freezing or above 30°C.

Extreme high temperature events are also responsible for highly publicized weather impacts such as heat-wave mortality. Karl and Knight (1997) found that elevated nighttime apparent temperatures (an index of both temperature and humidity) coupled with a variety of societal factors (Changnon, et al. 1996) were responsible for the impacts of the unusual and deadly heat wave that gripped Chicago, Illinois during the summer of 1995. Prior to 1995 the trends of elevated nighttime apparent temperatures had only slightly increased in the Central USA, making the 1995 event even more unusual.

Aside from the few examples cited above, there is a surprising dearth of analyses addressing changes in extreme temperatures. Perhaps partly because temperature is generally regarded as following a normal distribution, relatively few analyses of changes in growing seasons and temperature extremes have been undertaken. Many who have addressed this issue (Karl and Knight, 1997; Katz and Brown, 1992, Mearns et al., 1984) have generally applied normal distribution functions to their analyses, and made inferences about changes in the extremes of temperature, based on changes in the mean.

So, perhaps the greatest uncertainty about changes in temperature extremes for any specific location relates to the properties of extremes themselves. Although it is true that temperatures approximate a normal distribution, where the behavior of extremes ought to be well-approximated from changes in the mean, the data suggest that such inferences cannot consistently be relied upon. For example, despite an increase of mean temperatures in the USA of about 0.4 °C over the past Century, annual extreme maximum has decreased by 0.2 °C, while the annual extreme minimum increased by the same amount. In the former USSR, the contrast is also most apparent during the spring. For example, Karl et al. (1991) found an increase in the spring **mean** minimum temperature, averaged across the country, of 1.4 °C from 1951-1986, but the **1-day extreme** minimum temperature increased by 2.2 °C, and both increases were statistically significant. This suggests that even a relatively minor increase in mean temperature may result in more frequent extremes, for example more heat waves or more extreme cold events.

For extremes, Katz and Brown (1992) point out that changes in the variability are more important than changes in the mean. IPCC (1996) comprehensively discusses what is known about changes in temperature variability. Since variability of temperature can be defined in several ways it is important to understand what aspects of variability are being analyzed. For example, the variance of the two series of 5,5,5,0,0,0,-5,-5-,5 and 5,-5,0,5-5,0,5,-5,0 representing annual anomalies are identical, but the absolute value of the interannual annual differences are quite dissimilar indicating a difference in persistence. In a global study, Parker et al. (1994) compared spatially averaged variances of annual temperature anomalies between the two periods 1974 to 1993 with 1954 to 1973 and found evidence for an increase in temperature variability in the 1974-1993 period of between 4 and 11% depending on the season. In some areas the increase was considerably larger, especially over North America. Karl, et al. (1995) analyzed changes in variability on a variety of times-scales from 1-day to 1-year for much of the Northern Hemisphere (USA, China, and the former USSR) during the Twentieth Century. Their analysis was based on the absolute value of time-averaged differences from one period to the next. Using this statistic they found evidence for a decrease in temperature variability on short time-scales (e.g., up to a few days), but no broad scale increases in interannual variability. Therefore, although the year-to-year variability may not be affected, this could have implications for the length of certain types of multi-day events, such as heat waves, or cold snaps.

2.2. PRECIPITATION

2.2.1. *Intense Precipitation*

There have been a number of large flooding events in the 1990's in Europe, Asia, and the United States that have highlighted a renewed emphasis on changes in precipitation extremes. Work resulted from this renewed emphasis is beginning to suggest that there have been some important changes and variations related to a variety of precipitation extreme statistics. Recent work by Groisman et al. (1999) provides a framework for understanding a number of recent analyses that have pointed toward an increase in precipitation extremes in North America, portions of Europe, Japan, Australia, South Africa, the former Soviet Union, and elsewhere (IPCC, 1996). Groisman et al. (1999) demonstrate, using daily precipitation data from North America, a large portion of Asia, portions of Europe, and Austalia that any change in the mean monthly total precipitation will influence the extremes more than any other precipitation rate. With an increase in total precipitation, a disproportionate increase in precipitation for higher daily precipitation rate is expected, compared to more moderate precipitation rates. However, changes in the total number of raindays remains somewhat inconclusive..

IPCC (1996) has demonstrated that precipitation has generally increased across much of the mid-to-high latitude land areas during the past Century. Karl and Knight (1998) find a very significant increase in extreme precipitation events during the Twentieth Century in the USA. The increase has occurred due to both an increase in the frequency of very heavy and extreme precipitation events as well as an increase in their intensity. Similar analyses for the USA have now been run for Canada (since 1941), the former Soviet Union (since 1967), and Australia (since 1910) with less striking changes, but clear evidence for an increase in heavy and extreme precipitation events. Extensions (Suppiah et al., 1997) of earlier work by Suppiah and Hennessy (1996), show that in Australia the 90th, 95th, and 99th percentiles of daily precipitation totals has increased by 20, 6, and 4% respectively, when averaged across the country. In a recent analysis of six long-term stations in Germany an increase in daily extreme precipitation amounts has also been detected in all but one of the stations, and the trends are statistically significant at three of the stations with increases during the Twentieth Century of over 25mm/day (Rösner et al., 1997). Over South Africa, Mason et al. (1998) indicate that significant increases in extreme rainfall events have taken place between the two 30-year periods, 1931-60 to 1961-90. The intensity of the 10-year high rainfall event has increased by over 10% over large areas of South Africa. Mason et al. (1998) find that percentage increases are largest for the heaviest rainfall events. Iwashima and Yamomota (1993) also found an increase in the likelihood of extreme precipitation events in recent decades in Japan.

There are regions however, were little or no change in the intensity or frequency of extreme precipitation events has been identified. For example, an analysis of 1-day, 2-day, and 3-day precipitation total in India do not reveal any general trend toward more intense events (Kumar, et al. 1997), as increases in the west are balanced by decreases in the east. Similarly, for China Zhai et al. (1999) do not find evidence for an increase in precipitation extremes for 1 and 3-day events, and there is little change in total annual precipitation in China. Analyses of changes in short-term precipitation extremes for the former Soviet Union have been limited to date due to data inhomogeneity problems (Karl and Knight, 1995), but IPCC

(1996) suggests a net overall increase in precipitation for this region of the world, which suggests that extreme precipitation amounts may have increased prior to 1967 (the beginning date of the Karl and Knight analysis).

2.2.2. *Droughts and Floods*

The question was posed by IPCC (1990) whether there has been a tendency for an increase in the area of the globe affected by droughts and floods. Analyses at that time showed little suggestion of an increase. More recent work however, e.g., (Karl et al., 1995) indicates that in the USA the increase in precipitation during the past few decades leading to more wet spells and floods has not been accompanied by commensurate decrease in the frequency or intensity of droughts. In other words, at least in the USA there has been an increase in the percent area of the country experiencing a climate extreme. In a broader analysis Dai et al. (1998) find that there has been an increase in the frequency and intensity of droughts or wet spells in areas that are influenced by ENSO. This is especially notable in the tropics and subtropics. Furthermore, Mantua, et al. (1998) have recently identified a long-period oscillation centered over the mid-latitude northern Pacific basin they have termed the Pacific inter-Decadal Oscillation (PDO). The PDO signature appears to be an irregular, but robust pattern of climate variability that varies on interannual to interdecadal time scales that is clearly related to ENSO. However it appears to be a longer period oscillation that envelopes shorter-period ENSO events, such that the late 1970's shift to more frequent and intense ENSO's may be a manifestation of the PDO (Mantua, et al. 1998).

2.3. STORMS

In this section a distinction is made between tropical and extratropical cyclones. Although both systems are associated with regional-scale cyclonic surface wind circulations around a low pressure system, tropical cyclones are not associated with frontal systems whereas extratropical cyclones feed off such frontal boundaries. Tropical cyclones are very much dependent on evaporation and sensible heat fluxes from the oceans for their energy sources.

2.3.1. *Tropical cyclones*

Tropical cyclones are the costliest natural disasters around the world. Landsea et al. (1997) provide a comprehensive review of the Twentieth Century changes in tropical cyclone frequency and intensity around the world. IPCC (1996) and Landsea (1999) find that tropical cyclone frequency is not generally increasing or decreasing when considered across the globe, but there is significant decadal variability associated with both the number and intensity of tropical cyclones. On a regional basis there is evidence for a significant increase in tropical cyclone frequency in the Northwest Pacific since the 1970s, but records back to 1960 suggest that tropical cyclone frequency was also high during the 1960s (Landsea, 1999). On average, this basin is responsible for over 30% of the global tropical cyclones that form each year. In the Atlantic basin, which contributes to about 12% of the global total number of tropical cyclones each year, there has been a decrease in hurricane intensity since the mid-1940s (when reasonably reliable records begin), but since the turn of the Century there is no overall trend in hurricane frequency. Similarly, for land-falling hurricanes affecting the USA, there are large inter-decadal variations, but little evidence for any systematic trends. This decrease since the 1940s is consistent with the increase in ENSO activity that occurred in the late 1970s. Landsea and Gray (1992) point out that during an El Nino event tropical cyclone activity in the Atlantic tends to be suppressed due to increased shear in the lower and middle troposphere. In the North Indian Ocean, data suggest a significant downward trend in tropical cyclone frequency (Landsea, 1999). In the Australian region the data indicates little change in the number and frequency (Nicholls, 1999) of intense tropical storms since records began in the 1960s. However, less intense storms show a decline that is attributable, at least in part, to inhomogeneities in the record (Nicholls, 1999). Similarly, no change in tropical cyclone variations have been detected in the Southwest Indian Ocean or the Southwest Pacific since the 1960s.

2.3.2. *Extratropical cyclones*

Once again there are a dearth of analyses on the trends of intense extratropical cyclones, and some analyses are conflicting in terms of their result. Only recently, does there seem to be some consistency regarding an overall increase in the intensity of the strongest cyclones. For example, an increase in storm intensity during the late 1980s and first half of the 1990s has been found by a number of investigators for the North Atlantic Ocean, e.g., Stein and Hense(1994), Kushnir et al. (1997). There appears to be an abrupt shift toward more intense storms in the northern half of the basin (with the exception of the past two winters), but a decrease in intensity in the southern half over the past several decades. Lambert (1996) analyzed intense cyclones in the N. Pacific and Atlantic and found evidence to support a strong increase in intensity during the past several decades. Similarly, Bardin (1994) reported that the size and intensity of cyclones has increased since 1980. Davis and Dolan (1993) find an increase in the number of intense cyclones over eastern North America, but decadal variability in this region is great, making it difficult to separate out a statistically significant trend.

3. Loss Reduction Prospects

Reducing the impact of extreme weather and climate on human suffering and economic losses is a high priority for the International Decade of Natural Hazard Reduction. A critical step toward reaching this goal relates to better knowledge of what the future climate might bring in the way of these natural hazards. Improved projections and confidence in them are dependent on understanding the causes and variations within the modern instrumental record. This requires considerable attention be given to the linkages between observed changes and specific causes (the attribution issue). It is also important to ensure proper utilization of existing and new data and information about expected changes in climate extremes in long-range planning and infrastructure maintenance. Both of these activities are critically dependent on our ability to monitor changes in climate and weather extremes.

3.1. ATTRIBUTION OF TRENDS

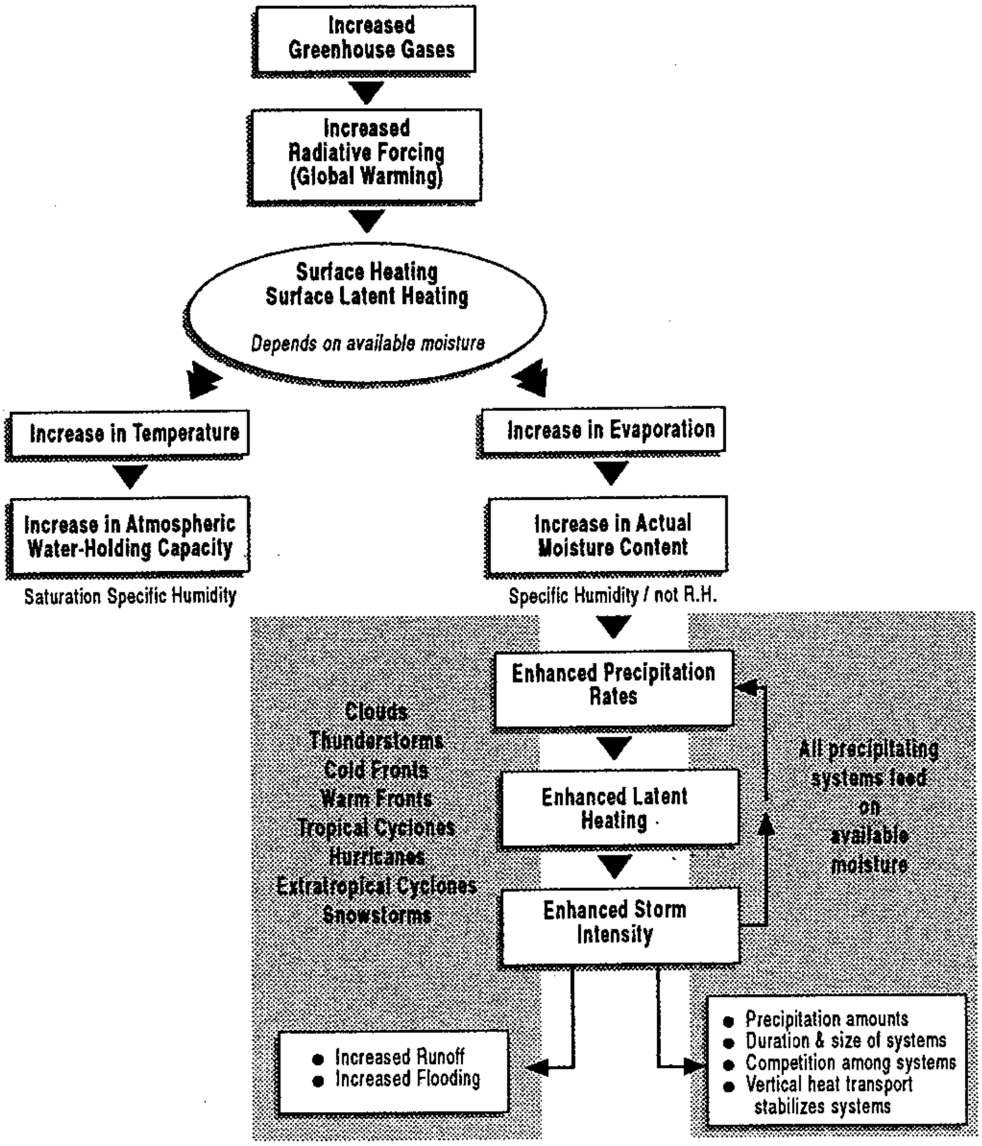
Clearly many, although not all, of the changes in temperature extremes we have examined here are related to increases in the global mean temperature. Since the overall increase in global mean temperatures is likely to be at least partially a result of increases of greenhouse gases (IPCC, 1996) there is reason to believe that the changes in temperature extremes may be related to these increases as well. The anthropogenic greenhouse effect related to changes in temperature variability are less certain, but there is some suggestion from climate models with enhanced concentrations of atmospheric CO_2 that short-term temperature variability would decrease, and this has been detected in several regions (Karl and Knight, 1995). Nonetheless the models are not entirely consistent in this regard (IPCC, 1996).

Perhaps one of the most critical attribution issues for changes in climate and weather extremes relates to the hypothesis that the hydrologic cycle should intensify as global warming progresses. Trenberth and Shea (1996) provide a conceptual model for such a hypothesis (Fig. 1). There are some indications, although by no means is the argument unequivocal, that the hydrologic cycle is growing more intense. In many instances the data is based on just a few decades with incomplete global coverage, so it is difficult at this stage to be comprehensive. Nonetheless, it is important to consider the changes and variations that have been observed related to an intensification of the hydrologic cycle. These changes are summarized below:

An increase in evaporation from the tropics (IPCC, 1996)

- Increase in convective clouds and related cirrus (IPCC, 1996)
- Increased continental cloud cover contributing to reduced diurnal temperature range and reduced evaporation from water surfaces over land (IPCC, 1996; Dai et al., 1997)
- Increased precipitation in the mid-and high-latitude land areas contributing to enhanced evaporation and more runoff (Dai et al., 1997)
- Increased atmospheric water vapor over North America, China, and tropical regions (IPCC, 1996; Ross and Elliott, 1996; Zhai and Eskridge, 1997)
- Increased precipitation intensity in many portions of the Northern Hemisphere (Karl and Knight, 1997; Groisman et al., 1999; Karl et al., 1997)

Figure 1-Conceptual model of the effect of greenhouse gases and global warming on the hydrologic cycle and phenomena associated with many climate extremes (from Trenberth and Shea, 1996).



- An increase in extratropical storm severity (Lambert, 1996)

Many of these changes are consistent with the conceptual model (Fig. 1) put forward by Trenberth and Shea (1996), and many of the changes have been projected to occur as global temperatures increase due to increases in atmospheric greenhouse gases, e.g., increased precipitation intensity, more precipitation in the mid- and high-latitudes, increased atmospheric water vapor etc.

Currently, there are a number of impediments preventing us from more effectively understanding the linkages between changes in climate extremes and natural hazards to anthropogenically-induced climate change. Certainly, model deficiencies are high among the list, but just as important is our lack of long-term reliable climate data. Time and time again, we find that our observing systems and data sets often have large systematic biases of uncertain magnitude casting doubt on our ability to detect multi-decadal changes. This is why efforts like the Global Climate Observing System (GCOS) are so critical.

3.2. BETTER USE OF EXISTING DATA

It is becoming increasingly apparent that even in the absence of clear attribution of the causes of the observed changes in the frequency and intensity of climate extremes we do not know how to address the problem of designing infrastructure for the next several decades in a climate that is clearly demonstrating that it is not stationary, even on decadal time scales. For example, what guidance can the climate community provide engineers who are designing for 100 and 200 year events? Clearly, one responsibility of the climate community is to convey to users of climate information that climate statistics, such as return period calculations, are based on past climate, and in some instances on relatively short periods. Therefore, the statistics do not contain any information on how these statistics may change in the future. As already pointed out, the extremes are far more sensitive to changes than changes in the mean. One can argue that it is now less desirable to design and plan for climate extremes by assuming the Twentieth Century climate will be a useful guide to the future, compared with projecting a different climate. Clearly, we have not explored the implications of such scenarios in terms of cost-benefit ratios. When does it pay to project modest changes versus strong changes or no change at all. This is an area of research that has not received adequate attention.

3.3. IMPROVED MONITORING AND DETECTION OF CHANGES IN EXTREMES

Improved monitoring, data management, and data diagnostics, as discussed in both IPCC (1990) and IPCC (1996) are critical to understand how the climate has changed and is changing or varying. The problem is even more sensitive for changes in climate extremes than changes in other climate statistics. There are a number of chronic problems related to long-term climate monitoring (Karl, 1995) that are now becoming acute. These are described and summarized below:

- International data exchange is being hampered due to cost recovery policies for high resolution historical climate records needed to estimate global changes of climate extremes. A step toward resolving this issue was recently taken by the jointly sponsored GCOS/CLIVAR international workshop on 'Indicators and Indices for Changes in Climate Extremes'. There is now an incipient effort to build joint databases suitable for analysis of changes in climate extremes including natural disasters. An institutional framework to encourage this fledgling effort has been requested by the scientists involved. Another suggestion proposed that the list of GCOS Global Surface Stations be used as a basis to develop and update a set of indices. They would provide considerable information about changes in climate extremes. These stations would have to provide statistics on at least daily resolution, updated annually.

- Considerable data on a variety of short-term (less than one month) weather and climate events remains inaccessible due to an absence of electronic digital data. An increase in emphasis on rescuing past measurements, with appropriate resolution, from deteriorating manuscripts and other non-electronic media is required to adequately quantify past changes in climate extremes. There are enormous collections of high resolution data related to precipitation, temperature, freezes, sea level pressure, etc. in addition to the metadata required to interpret these data that still reside in inaccessible media. Closer scientific linkages with projects like WMO's Data Rescue Project are called for to improve our information about changes high resolution climate extremes.

- Whether tropical cyclones occurrences are changing or precipitation is becoming more intense, the major problem affecting virtually every analysis relates to undocumented or unknown effects of inhomogeneities in data sets. A greater emphasis on removing inhomogeneities in the instrumental record and ongoing weather monitoring programs (that provide much of our information about changes and variations of weather and climate extremes) should take a high priority. Until weather observing networks and data management systems adopt and adhere to a set of climate monitoring principles it is unlikely the situation will improve. Such a set was recently recommended at a GCOS in-situ/space-based calibration validation meeting (Sept. 1996). A set of climate monitoring principles might include the following characteristics:

(1) Prior to implementing any changes in existing observing or data processing and management systems, an assessment should be completed related to the impact on our ability to monitor environmental variations and changes.

(2) Overlapping measurements, both in time and space for old and new observing systems should be standard practice for critical environmental variables whenever implementing changes in order to develop appropriate transfer functions from one system's measurements to the other .
(3)Calibration, validation, processing algorithms, knowledge of instrument, station and/or platform history, and any other information relevant to interpreting what is being measured are essential for data interpretation and use. This information should be recorded as a mandatory part of the observing routine and be archived with the original data.
(4)Routine assessment of both random and systematic errors is necessary to adequately monitor environmental variations and change.
(5)Environmental assessments that require knowledge of environmental variations and change should be well integrated into strategies for development and maintenance of Global Observing Systems.
(6) Observations with a long uninterrupted record should be maintained, and every effort should be made to protect the data sets that document long-term homogeneous observations.
(7) The highest priority in the design and implementation of new environmental observing systems should be given to data poor regions, variables and regions sensitive to change, as well as key measurements with inadequate temporal resolution.
(8) Network designers, operators, and instrument engineers must be provided environmental monitoring requirements at the outset of network design. Instruments must have adequate accuracy with biases small enough to resolve environmental variations and changes of primary interest.
(9) Much of the development of new observation capabilities and much of the evidence supporting the value of these observations stem from research-oriented needs or programs. Stable, long-term commitments to these observations, and a clear transition plan from research to operations, are two requirements in the development of adequate environmental monitoring capabilities.
(10) Data management systems that facilitate access, use, and interpretation are essential. Freedom of access, low cost, mechanisms which facilitate use (directories, catalogs, browse capabilities, availability of metadata on station histories, algorithm accessibility and documentation, etc.) and quality control (both random errors and systematic biases) should guide data management. International cooperation in all these areas is critical.

Some of the most effective means to monitor extreme weather and climate events relate to more effective use of space-based measurements and reanalysis products derived from climate models. Re-analysis products may be quite effective in analyses of extreme extratropical cyclones. This is clearly critical in the area of monitoring tropical cyclones, but improved estimates of precipitation from satellite and radar coverage are likely with careful integration of in-situ measurements. If programs such as the Global Precipitation Project were encouraged to focus more on time series of high resolution precipitation events this would help in identifying changes in climate extremes.

At the present time there are very few analyses of local extreme weather events such as tornadoes, hail, lightning, and wind. This at least partially reflects the inattention that has been given to these phenomena as part of multi-decadal climate monitoring. Since these phenomena are of vital importance to society and ecosystems, they must receive greater climatological emphasis in routine weather monitoring. At the present time for example, it is impossible to ascertain whether there has been any change in tornado frequency because of the inhomogeneities in reporting tornadoes during the past several decades. New networks, such as lightning detection contain many time-related biases due to changing configurations.

At the present time there are few venues to integrate and communicate information about what we know and do not know about changes in climate extremes. A step forward has been taken in this area with the joint sponsorship (GCOS/CLIVAR) of the recent meeting on "Indicators and Indices for Changes in Climate Extremes" which brought together an international group of scientists, and representatives from industry, all focused on developing data and information to document changes in climate extremes. The continuation and development of this initial effort, and others like it, are critical for effective data and information exchange outside of specialty fields.

4. Conclusions

Several important questions have been posed regarding climate extremes and natural hazards, some of which we do not yet have satisfactory answers. Existing data indicates that the climate is becoming more extreme in some areas and for some variables, but at this time it is difficult to unambiguously link such changes to anthropogenic effects. Nonetheless, there is beginning to emerge some hints that the global hydrologic cycle may be intensifying in response to global temperature increases. Inadequate data access and poor climate monitoring practices are two primary issues that must be improved if we expect to make much progress in this area. Climate monitoring can no longer be relegated to weather operations, but the scientific basis, rationale, and oversight for long-term monitoring of climate and weather extremes must be given a high priority in future WCRP activities.

Acknowledgments

The comments of Dr. Roger Pielke, Jr. and an anonymous reviewer are gratefully acknowledged. Partial support for this work was provide by NOAA's Climate Change Data and Detection Program Element of the Office of Global Program's Climate and Global Change Program and by a U.S. Dept. of Energy Interagency Agreement.

References

Bardin, M. Yu., 1994: Parameters of cyclonicity at 500 mb in the Northern Hemisphere extratropics. In Proc. XVIII Climate Diagnostics Workshop, Boulder, CO., NTIS, US Dept. of Commerce, Sills, Building, 5285 Port Royal Road, Springfield, VA 22161, U.S.A., pp 397.

Changnon, S.A., Kunkel, K.E., and Reinke, B.C.: 1996, Impacts and responses to the 1995 heat wave: A call to action, *Bull. Amer. Meteor. Soc.*, 77, 1497-1506.

Cooter, E.J. and LeDuc, S.K.: 1995, 'Recent frost date trends in the northeastern United States', *Int. J. Climatology*, **15**, 65-75.

Dai, A., Trenberth,K.E., and Karl T.R.: 1997, 'Hydrological control of diurnal temperature range', *Geophys. Res. Letts.*, in press..

Dai, A., Trenberth, K.E., and Karl, T.R.: 1998, 'Global variations in droughts and wet spells', *Geophys. Res. Letts.*, **25**, 3367-3370.

Davis, R.E., and Dolan, R.: 1993, ' Nor'easters', *American Scientist*, **81**, 428-439.

Downton, M.W. and Miller, K.A.: 1993, 'The freeze risk to Florida citrus. Part II: Temperature variability and circulation patterns', *J. Climate*, **6**, 364-372.

Easterling, D.R., Horton, B., Jones, P.D., Peterson, T.C., Karl, T.R., Parker, D.E., Salinger, M.J., Razuvayev, V., Plummer, N, Jamason, P., and Folland, C.K.: 1997, 'Maximum and minimum temperature trends for the globe', *Science*, 277, 364-367.

Easterling, D.R.: 1999, 'Recent trends in temperature extremes and threshold exceedences in the United States', submitted to, *Bull. Amer. Meteor. Soc.*

Easterling, D. R., Diaz, H.F., Douglas, A.V., Hogg, W.D, Kunkel, K.E., Rogers, J.C., and Wilkinson, J.F.: 1999, 'Long-term observations for monitoring extremes in the Americas', Workshop Proceedings on Indices and Indicators for Climate Extremes, Asheville, NC. Sponsors, CLIVAR, GCOS and WMO. *Climatic Change,* this issue.

Groisman, P. Y., Karl, T.R., Easterling,D.R., Knight, R.W., Jamason, P.F., Hennessy, K.J., Suppiah, R., Page, C.M., Wibig, J., Fortuniak, K, Razuveav, V., Douglas, A, Forland, E, and Zhai, P-M.: 1999, 'Changes in the probability of heavy precipitation: Important indicators of climatic change', Workshop Proceedings on Indices and Indicators for Climate Extremes, Asheville, NC. Sponsors, CLIVAR, GCOS and WMO. *Climatic Change,* this issue.

Intergovernmental Panel on Climate Change (IPCC), 1990: *Climate Change, Working Group 1 to the Intergovernmental Panel on Climate Change Scientific Assessment.* Houghton, J.T., Jenkins G.J., and Ephraums, J.J., editors. Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC), 1996: *Climate Change, Working Group 1 to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K., editors. Cambridge University Press.

International Federation of Red Cross and Red Crescent Societies (IFRCRCS) , 1997: *World Disasters Report 1997*, Oxford University Press, p 116.

Iwashima, T. and Yamamoto, R.: 1993, 'A statistical analysis of the extreme events: Long-term trend of heavy daily precipitation'. *J. Met. Soc. Japan*, **71**, 637-640.

Karl, T. R., Kukla, G., Razuvaev, V.N., Changery, M.J., Quayle, R.G., Heim, R.R., Easterling,D.R., and Fu, C.B.: 1991, 'Global Warming: Evidence for asymmetric diurnal temperature change', *Geophys. Res. Lett.*, **18**, 2253-2258.

Karl, T.R., Knight, R.W., and Plummer, N.: 1995, 'Trends in high-frequency climate variability in the twentieth century', *Nature*, **377**, 217-220.

Karl, T. R., Nicholls, N., and Gregory, J.: 1997, 'The Coming Climate', *Scientific American*, **276**, 54-59.

Karl, T.R. and Knight, R.W.: 1997, 'The 1995 Chicago Heat Wave: How likely is a recurrence', *Bull. Amer. Meteor. Soc.*, **78**, 1107-1119.

Karl, T. R. and Knight, R.W.: 1998, 'Secular trends of precipitation amount, frequency, and intensity in the USA', *Bull. Amer. Meteor. Soc.*, 79, 231-242.

Katz, R.W. and Brown B.G.: 1992, 'Extreme events in a changing climate: Variability is more important than averages. *Climatic Change*, **21**, 289-302.

Knovitz, J.: 1990, Why cities don't die, *Amer. Hert. Inv. Tech.*, **5**, 59-63.

Kumar, K.K., Deshpande, N.R., and Kumar, K.R.: 1997, 'Long-term changes in the heavy rainfall events over India', Workshop Proceedings on Indices and Indicators for Climate Extremes, Asheville, NC. Sponsors, GCOS/CLIVAR and WMO.

Kushnir, Y., Cardone, V., Greenwood, J., and Cane, M.: 1997, ' On the recent increase in North Atlantic wave heights', *J. Climate* 2107-2113.

Lambert, S. J.: 1996, ' Intense extratropical Northern Hemisphere winter cyclone events: 1899-1991', *J. Geophys. Res.*, **101**, 21319-21325.

Landsea, C. W. and Gray, W.M.: 1992, Associations of Sahel monsoon rainfall and concurrent intense Atlantic hurricanes, *J. Climate*, **5**, 435-453.

Landsea, C.W.: 1999, 'Atlantic basin hurricanes: Indices of climatic changes', Workshop Proceedings on Indices and Indicators for Climate Extremes, Asheville, NC. Sponsors, CLIVAR, GCOS and WMO. *Climatic Change*, this issue.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. : 1998, 'A Pacific interdecadal climate oscillation with impacts on salmon production', *Bull. Amer. Meteor. Soc.*, 78, 1069-1079.

Mason, S.J., Waylen, P.R., Raiaratma, B., and Harrison, J. M.: 1998, 'Changes in extreme rainfall events in South Africa', *Climatic Change*. In press.

Mearns, L. O., Katz, R. W., and Schneider, S. H.: 1984, ' Extreme high-temperature events: Changes in their probabilities with changes in mean temperature', *J. Clim. Appl. Meteorol.*, **23**, 1601-1613.

Mitchell, J.K.: 1990, 'Natural hazards predictions and reponses in very large cities', in *Prediction and Perception of Natural Hazards*, Nemic, et al. (Eds.), Dordrecht, The Netherlands, pp. 29-37.
Munich Re, 1996: Annual review of natural catastrophes 1996. *Topics*, 1-16.

Nicholls, N.: 1997, 'CLIVAR and IPCC interests in extreme events', Workshop Proceedings on Indices and Indicators for Climate Extremes, Asheville, NC. Sponsors, CLIVAR, GCOS and WMO.

Parker, D.E., Legg, T.P., and Folland, C.K.: 1994, 'Interdecadal changes of surface temperatures since the late 19th century', *J. Geophys. Res.* **99**, 14373-14399.

Pielke, R.A., Jr., and Landsea, C.W.: 1998, 'Normalized hurricane damages in the United States: 1925-1995', *Weather and Forecasting*, in press.

Plummer, N., Nicholls, N., Lavery, B.M., Leighton, R.M., and Trewin, B.C.: 1999, 'Twentieth century trends in Australian climate extremes indices', Workshop Proceedings on Indices and Indicators for Climate Extremes, Asheville, NC. Sponsors, GCOS/CLIVAR and WMO, *Climatic Change* this issue.

Rogers, J.C. and Rohli, R.V.: 1991, 'Atmospheric teleconnections and citrus freezes in the Great Plains', J. Climate, **4**, 1103-1113.

Rösner, S., Muller-Westermier, G., and Rosenhagen, G.: 1997, 'German data for indices/indicators for changes in extreme events', Workshop Proceedings on Indices and Indicators for Climate Extremes, Asheville, NC. Sponsors, GCOS/CLIVAR and WMO.

Ross, R.J. and Elliott, W.P.: 1996, 'Tropospheric water vapor trends over North America: 1973-93', Submitted *to J. Climate.*

Salinger, J.M.: 1997, 'Indices and indicators of changes in extreme events in the South Pacific preliminary results from New Zealand', Workshop Proceedings on Indices and Indicators for Climate Extremes, Asheville, NC. Sponsors, GCOS/CLIVAR and WMO.

Schneider, S.H.: 1998, 'Kyoto protocol: The unfinished agenda.' *Climatic Change*, **39,** 1-21.

Stein, O. and A. Hense: 1994, 'A reconstructed time series of the number of extreme low pressure events since 1880', *Meteorol Zeitschrift,* **N.F. 3,** 43-46.

Suppiah, R. and Hennessy, K. J.: 1996, 'Trends in intensity and frequency of heavy rainfall in tropical Australia and links with the Southern Oscillation', *Aust. Meteorol. Mag.*

Suppiah, R. and Hennessy, K. J.: 1997, 'Indices of changes in intense precipitation for Australia', Workshop Proceedings on Indices and Indicators for Climate Extremes, Asheville, NC. Sponsors, GCOS/CLIVAR and WMO.

Trenberth, K.E. and D.J. Shea: 1996, 'Atmospheric circulation changes and links to changes in rainfall and drought', 7th Conference on Climate Variations, American Meteorological Society, Long Beach, CA. J14-J19.

Zhai, P., S. Anjian, F. Ren, B. Gao, Q. Zhang, and X. Liu: 1999, 'Changes of climate extremes in China', Workshop Proceedings on Indices and Indicators for Climate Extremes, Asheville, NC. Sponsors, GCOS/CLIVAR. *Climatic Change,* this issue.

Zhai, P. and R. Eskridge: 1997, 'Atmospheric water vapor over China', *J. Climate*, 10, 2643-2652.

(Received 5 November 1997; in revised form 16 November 1998)