





Climate Extremes: Changes, Impacts, and Projections

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Elements of Change Series

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Acronyms
Units

Acronyms

AASC	American Association of State Climatologists
AMP	Adaptive Management Program
CAFE	Corporate Average Fuel Economy
CEQ	White House Council on Environmental Quality
DTR	diurnal temperature range
ENSO	El Niño/Southern Oscillation
GCD	Glen Canyon Dam
GCM	General Circulation Model or Global Climate Model
GCOS	Global Climate Observing System
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
MPI	maximum potential intensities
MSU	Microwave Sounding Unit
NASA	National Aeronautics and Space Administration
NAST	National Assessment Synthesis Team
NAWG	National Assessment Working Group
NCDC	National Climatic Data Center
NCEC	National Climate Extremes Committee
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
NSF	National Science Foundation
OLR	outgoing longwave radiation
PDO	Pacific inter-Decadal Oscillation
PDSI	Palmer Drought Severity Index
RCC	Regional Climate Center
SST	sea surface temperature
TOMS	Total Ozone Mapping Spectrometer
USGCRP	U. S. Global Change Research Program
WMO	World Meteorological Organization
WX CATS	adjusted catastrophies

Units

ha	hectare
hPa	hecto Pascal
MAF	million acre feet
mb	millibar

Chair's Essay:
Climatic Extremes: Changes, Impacts, and Projections

Thomas Karl
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David Easterling
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There is general agreement that changes in the frequency or intensity of extreme weather and climate are likely to have profound impacts, both ecologically and on human society. These changes may be long-term trends or decadal fluctuations, and distinguishing between the two is a major issue which we can only address with the use of both model simulations and analysis of the past climate record.

Understanding the linkages among climate and weather extremes and their impact on societies' infrastructure, and on managed and natural ecosystems, are areas of major uncertainty. This is highlighted by sectoral and regional differences in responses to the impacts of weather and climate extremes. Teasing out these relationships between the physical climate system and its impacts is a major focus of the U. S. National Climate Change Assessment that is underway.

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The Aspen Global Change Institute summer meeting on Climate Extremes brought together modelers, climate monitoring diagnosticians, and climate impact experts (social scientists and ecologists) to better understand this interdisciplinary issue. A number of questions were posed and discussion focused around these issues:

Climate Models
What do climate model simulations tell us about past and projected changes in climate and weather extremes, given past and projected changes in radiative forcing?

Observations
What does the observational record indicate about changes in weather and climate extremes?

Climate Impacts
What do we know about the sensitivity of various systems (both human and ecological) and the dependence among systems related to the frequency and intensity of weather and climate extremes?

For all areas
What are the major uncertainties and the highest research and monitoring priorities?
What are the impediments to linkages among these three areas of research, and how might they be resolved?

As was anticipated by the meetings' Chairs, the AGCI groups' collective insights have been summarized in a set of review articles which have been submitted for publication in *The Bulletin of the American Meteorological Society (BAMS)*. A summary of these insights follows for issues of modeling, observations, societal impacts, and ecological impacts of climatic extremes. For the complete versions of these articles, including more detail and examples, and accompanied by their full sets of references, see the forthcoming series in *BAMS*: "Trends in Extreme Weather and Climate Events," a set of papers: "Issues Related to Modeling Extremes in Projections of Future Climate Change," Gerald A. Meehl, Francis Zwiers, Jenni L. Evans, Thomas Knutson, Linda Mearns, Peter Whetton; "Observed Variability and Trends in Extreme Climate Events," David R. Easterling, Jenni L. Evans, Pavel Ya. Groisman, Thomas R. Karl, Kenneth E. Kunkel; "Societal Impacts of Extreme Events," Stanley Changnon, Roger A. Pielke, Jr., David Changnon, Richard T. Sylves, and Roger Pulwarty; "Issues Related to Terrestrial Ecological Impacts," Camille Parmesan and Terry Root. A review article based on the above is also in preparation for submittal to *Science*.

We would expect an increase of intense precipitation and more rainfall from a given storm, both results seen in climate model simulations.

Modeling Climate Extremes

Many of the model studies of weather and climate extremes in a future climate with increased greenhouse gases agree with intuitions from our understanding of how the climate system works. For example, a warming of the surface supplies more water vapor to the atmosphere, thus making more moisture available in storms. We would therefore expect an increase of intense precipitation and more rainfall from a given storm, both results seen in climate model simulations.

Additionally, a number of changes in weather and climate extremes from climate models have been seen in observations in various parts of the world (decreased diurnal temperature range, warmer mean temperatures associated with increased very warm days and decreased very cold days, increased rainfall intensity, etc.). Though the climate models can simulate many aspects of climate variability and extremes, they are still characterized by systematic simulation errors and limitations in accurately simulating regional climate such that appropriate caveats must accompany any discussion of future changes in weather and climate extremes.

Recent studies have reproduced some of the previous results reported by the Intergovernmental Panel on Climate Change and this gives us increased confidence in their credibility (though agreement between models does not guarantee those changes will occur in the real climate system):

1) An increase in mean temperatures leads to more extreme high temperatures and less extreme low temperatures, and has been related to an increase in a heat index (leading to increased discomfort and stress on the human body), an increase in cooling degree days and decrease in heating degree days.
2) Night-time low temperatures in many regions increase more than day-time highs, thus reducing the diurnal temperature range.
3) Decreased daily variability of temperature in winter and increased variability in summer in northern hemisphere midlatitude areas significantly modify changes in extremes.

4) Increased moisture content in many regions contributes to increased precipitation intensity, with return time for 20-year extreme precipitation events reduced to 10 years in some regions.
5) Indian monsoon variability tends to increase, thus increasing the chances of extreme dry and wet monsoon seasons.
6) There is a general drying of the northern hemisphere midcontinental areas during summer with increased chance of drought. This is ascribed to a combination of increased temperature and decreased precipitation.
7) Several global climate models indicate that the future mean Pacific climate base state could more resemble an El Niño-like state (*i. e.*, a slackened west-east sea surface temperature gradient with associated eastward shifts of precipitation), though that result remains model-dependent. For such an El Niño-like climate change, future seasonal precipitation extremes associated with a given El Niño would be more intense due to the warmer mean base state.

Additional aspects have been addressed in model studies, but remain unresolved at this time:
1) There is little agreement between the models concerning the possible future behavior of midlatitude storms, their intensity or frequency changes or storm track changes. However new studies have pioneered techniques to study such changes, and with improved models additional information may soon be available.
2) Due to the difficulties of spatial resolution, there is virtually no information available from climate models at present to indicate possible future changes of thunderstorms and tornadoes.
3) Decadal and longer time scale variability complicate assessment of future changes in individual El Niño events in terms of their amplitude and frequency, and assessment of such possible changes remains quite difficult.
4) Studies of future changes in tropical cyclone frequency remain inconclusive, with some studies suggesting the possibility of more intense tropical cyclones in the future. Progress has been made in studying changes in tropical cyclones with embedded regional high resolution models, and those types of studies hold promise for better estimates of future tropical cyclone behavior.

Exponentially increasing economic loses, coupled with a moderate increase in deaths due to these events, have focused attention on the possibility that these events are increasing in frequency.

Observations of Climate Extremes

Variations and trends in extreme climate events have only recently received much attention. Exponentially increasing economic loses, coupled with a moderate increase in deaths due to these events, have focused attention on the possibility that these events are increasing in frequency. Here we address extreme climate events in the observed record by defining what we mean by climate extremes, what kinds of data are required to analyze variability and trends in these events, and what we know about recent variability and changes in these events over the 20th century. A major problems in examining the climate record for changes in extremes is a lack of high quality long-term data. Nonetheless, recent analyses of a variety of climate extremes suggest that in some areas of the world there are statistically significant increases, but this varies considerably across variables.

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, and that this increase is due to a stronger warming in minimum temperatures than maximums. Global precipitation has also increased over the same period. Given these increases, it is expected that there would also be increases in what are now considered extreme events.

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 be monetary, or may involve excessive loss of life, such as that due to Hurricane Mitch in Central America in October of 1998. Here we restrict our examination to those types of events defined only using climate data and for which we can realistically expect to obtain the long-term data necessary to examine recent variability and changes in these events. This includes extreme temperature events, both in terms of absolute daily extremes and derived variables such as growing season length, apparent temperature and drought, single and multi-day extreme precipitation events, and tropical and extratropical storms.

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 20th century.

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 20th century either worldwide or regionally. This includes high temporal and spatial resolution observations of temperature, precipitation, humidity, winds, atmospheric pressure, and a host of other meteorological variables for many parts of the world. Analyses of precipitation extremes for most countries has only taken place since WWII, but in Australia, the U. S., Norway, and South Africa, analyses began near the start of the 20th century.

Most climatological observing stations record data at least once a day, including maximum temperature, minimum temperature, and total precipitation for the previous 24 hour period. However, it is estimated that less than 5% of precipitation reporting stations' data are freely available for international data exchange. Often the daily data are not in digital form. Even in the U. S., a large quantity of these data for the period prior to 1948 are only now being digitized. Furthermore, even if the data are available, issues of quality control and homogeneity must be considered since both can affect an analysis of extreme events. Below we summarize information about changes in various extreme events over the globe without pretending to be comprehensive as we focus on those variables and regions for which data are electronically accessible without restriction.

Temperature

Relatively little work has been competed related to changes in high frequency extreme temperature events. This includes heat waves, cold waves, and number of days exceeding various temperature thresholds. Easterling examined trends in the number of days exceeding thresholds of 0°C, 32.2°C (90°F), and percentile thresholds. Trends indicate that for the 20th century, there has been a slight decrease in the number of days below freezing over the entire U. S. 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. Two other studies focused on the Northeastern U. S. support the notion that changes in the number of days exceeding thresholds have occurred, resulting in fewer days below freezing and an increase in the frost-free season. Apparent temperature is another important measure, particularly for human health. One recent study shows regional changes in days exceeding threshold apparent temperature such as the 80th percentile value in the U. S., with the Southeastern and Southwestern U. S. exhibiting signs of increases in apparent minimum temperature.

Short-duration episodes of extreme heat or cold are often responsible for 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. Although this heat wave was one of the worst short-duration events of the 20th Century, an analysis of multi-day extreme heat episodes where the temperature exceeds the 10-year return threshold does not show any overall trend for the period of 1931-1997. 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. Extreme cold waves analyzed the same way also show no overall U. S. trend since 1931.

Precipitation

Trends in one-day and multi-day extreme precipitation events in the U. S. and other countries show a tendency to more days with extreme 24-hour precipitation totals. The number of days annually exceeding 50.8 mm (2 inches) of precipitation has been increasing in the U. S. 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. 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.

Over most regions there has been an increase in seasonal or annual precipitation totals that relates to a disproportionately greater increase in heavy precipitation.

Analyses of heavy precipitation events for other parts of the world indicate that for 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. Similar patterns have been found for the United Kingdom where increases in heavy wintertime events and decreases in heavy summertime events have been found. 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. An increase in humidity over the European part of the former USSR since late 1970s has been reported, related to an increase in precipitation, stream flow and the level of the Caspian Sea.

In most countries that have experienced an increase in monthly or seasonal precipitation, this increase has been directly related to an increase in the amount of precipitation falling during the heavy and extreme precipitation events. Over most regions there has been an increase in seasonal or annual precipitation totals that relates to a disproportionately greater increase in heavy precipitation.

Drought and Wet Periods

An important aspect of climate extremes is related to excessive drought or wet periods. Recent analyses show increases in the overall areas of the world affected by either drought or excessive wetness. Examination of drought over the 20th century in the U. S. shows that there is considerable variability, with the droughts of the 1930s and 1950s dominating any long-term trend. Recent investigation of longer-term variability over the past 2000 years using paleoclimatic data indicates that large droughts, such as those of the 1930s, can be expected to occur once or twice per century in the Central U. S., and that multi-decadal mega-droughts extending over larger areas occur every few hundred years.

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. This is consistent with long-term increases in annual precipitation, and increases in heavy precipitation events. Analysis of drought for Hungary shows an increasing trend in droughts, with a decrease in wet spells. Over China, a long-term decrease in mean precipitation has been accompanied by an increase in the area of droughts and a decrease in the area with excessive precipitation.

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Tropical Storms

Occurrences of Atlantic hurricanes show no real long-term trend over the 20th century. However, large variations of hurricane activity on interdecadal time scales have been observed in this century. 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.

Hurricane impacts are not restricted to the Southeastern U. S. 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 U. S. 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.

Climate Extremes Index

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.* 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 1970s the Index has remained high, suggesting that the U. S. is experiencing more of these types of extremes.

In summary, it is clear that for most areas where analyses of extreme events have taken place, significant changes are occurring. This is especially true in heavy precipitation events

where for most areas analyzed there have been significant increases in short-term extreme events. This also appears to be the case in some temperature events, particularly in the U.S. There is still much work to be done in determining whether significant large-scale changes in these types of events are occurring around the globe. As discussed above, a key issue is the lack of access to high-quality, long-term climate data with the time resolution appropriate for analyzing extreme events. These problems must be overcome to be able to make definitive statements regarding long-term changes in extreme events. Additional details on observations of extreme events can be found in Tom Karl's presentation summary in this volume.

Impacts of Climate Extremes on Society

Recent years have seen a tremendous increase in economic losses from weather hazards. Since 1987, each of more than 360 U. S. weather events produced losses in excess of $5 million. Record setting catastrophes included the drought of 1988-1989 with losses reaching $39 billion, Hurricane Andrew in 1992 ($30 billion), and the flood of 1993 ($19 billion). These losses and their underlying causes have become the major focus of the insurance industry in the U. S. and beyond. The damages from these events also brought forth record government payments for relief and assistance at a time when controlling the budget has become a national goal. The 1995 heat wave killed 1,100 persons, awakening society to another growing atmospheric threat.

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These weather losses helped raise alarm over the possibility that the recent increases were due to a shifting climate. There has long been scientific concern that a change in climate due to anthropogenic activities would include an increase in the frequency and/or intensity of weather and climate extremes. Changes in either could have major societal impacts. The IPCC addressed the issue on a global scale in its 1995 assessment, declaring "Overall, there is no evidence that extreme weather events, or climate variability, has increased in a global sense through the 20th Century." Regardless of the potential relationship to global warming, the trends in losses provide strong motivation for the government and weather-sensitive commerce and business interests to better define and identify the causes of the trends in weather extremes in order to respond effectively.

Trends in Losses

Losses caused by catastrophes, defined by the property insurance industry as storms causing insured losses greater than $5 million in the year of occurrence, have grown steadily from about $100 million annually in the 1950s to $6 billion per year in the 1990s, and the annual number of catastrophes grew from 10 per year in the 1950s to 35 annually in the 1990s. The 1990-1997 total insured property losses were $49 billion, and federal relief payments for weather-caused disasters were $12 billion. The 1990s experienced a record number of damaging storms. Federal relief payments for weather disasters grew from $670 million in 1966-1970 (in 1994 dollars) to $4 billion in 1991-1995.

Losses created by various weather types have also grown. Annual hurricane losses went from $5 billion in the 1940s to more than $40 billion in the 1990s (adjusted for inflation to 1990 dollars). Flood damages, which rank as the top weather-caused losses in the nation,

also continue to increase with annual losses of $1 billion in the 1940s, growing to $6 billion per year (all in 1997 dollars) during the 1980s-1990s. Damaging hailstorms causing urban losses in excess of $300 million have become common in the 1990s as evidenced by record storms in Denver, Dallas, Oklahoma City, Wichita, Orlando, and Ft. Worth. Trends in losses also show sharp regional differences. Much greater increases have occurred along the West Coast, in the Southwest, and in the Southeastern coastal states than elsewhere.

Weather-related loss of life has not shown the overall increase found in dollar losses. The number of deaths related to tornadoes, hurricanes, and severe storms have either decreased or remained unchanged over the past 20 years. The lack of an increase in weather deaths, given an ever growing population, is largely attributed to better forecasting, improved warning systems, and greater awareness of risks. The only weather hazards showing increases in mortality have been those due to flooding and to heat waves.

There is no single source of data on all types of financial losses caused by weather extremes or any other type of natural disasters. It is often difficult to find systematic data on losses since many storm damages go unrecorded and must be estimated. Insurance loss data and government relief-assistance payments are systematic sources of data, but many uninsured losses are experienced by individuals and business and it is difficult to get accurate estimates of these losses. Determination of the economic losses caused by extreme conditions requires assessment of many data sources, adjustment of the data for temporal changes in inflation and other factors affecting losses, and combination of a variety of data and information to obtain a composite measure of the total direct and indirect losses.

Losses caused by catastrophes (>$5 million in losses) have grown steadily from about $100 million annually in the 1950s to $6 billion per year in the 1990s, while the number of catastrophes grew from 10 per year to 35.

Trends in most storm loss data, after careful adjustment for societal and insurance factors, do not display upward trends with time, but rather are flat trends with random-appearing fluctuations over the past 40 to 60 years. When this information is compared with the sharp upward trends in actual dollar losses, and when this information is coupled with the locations of where the losses have grown the most (southeast, south, and west), the results collectively indicate that the major cause of trends in losses related to weather and climate extremes is societal factors: the growth of wealth with more valuable property at risk, increasing density of property, and demographic shifts to coastal areas and storm-prone areas which are experiencing increasing urbanization.

Studies regarding deaths caused by heat waves have found that changes in certain societal factors such as age and poverty level largely explain why recent heat waves have caused more deaths than those from earlier strong heat waves. The continuing growth in deaths caused by floods is also partly the result of social behavior, and whether the actual increases in hydrologic floods contribute to this remains an open question. Thus, the results from most studies show there has been an overall increase in the nation's vulnerability to weather and climate extremes.

Loss trends can also be a function of shifts in extreme weather-climate events. However, recent investigations of trends in damaging storm activity reveal that for many weather extremes including hailstorms, thunderstorms, tornadoes, droughts, and hurricanes, there

were no long-term increases during the last 30 to 50 years comparable to the observed trends in losses.

In summary, societal impacts from weather and climate extremes, and trends in those impacts, are a function of both climate and society. Comprehensive assessments of losses and results from several recent studies of extremes establish that losses related to most weather-climate extremes have been on the rise. But, after adjustment of the data for major societal changes, most losses from weather-climate extremes are not increasing. This indicates that most upward changes are due to a mix of societal factors. Geographical location of the large loss trends further reveal that population growth and demographic shifts are playing a major role in the degree of increasing losses from weather-climate extremes.

The United States is becoming ever more vulnerable to extremes. Even with large expenditures on technology-based systems, and without major changes in societal responses to weather and climate extremes, it is reasonable to predict ever-increasing losses even without any detrimental climate changes. Any climate changes would exacerbate the existing vulnerability. Recognition of these trends in societal vulnerability to weather extremes suggests that the present focus on mitigating climate change should be complemented by a greater emphasis on adaptation. Although it is difficult and often expensive to gain a reasonably accurate measure of weather losses, it is essential to develop and maintain a clear picture of the impacts and their trends for policy, planning, and mitigative activities. Identifying and understanding this societal vulnerability has great advantages: it allows society to avert future losses through adapting to and preparing for the vicissitudes of weather and climate extremes.

Terrestrial Ecological Impacts of Climate Extremes

Climate drives biotic systems. Climatic events affect individual fitness, population dynamics, and whole species distributions and abundance patterns. Regional variation of climatic regimes are part of the suite of local selective pressures that promote the evolution of exterior color and surface patterns, body shape and size, and behaviors. Many of these adaptations help the organism to modify or tolerate extreme temperatures. Precipitation and solar insolation are essential resources for growth in plants. Effects of climate on plant population dynamics radiate through food webs as plant life provides resources for herbivores, and they to their predators, and so on to the top carnivores. Additionally, all plants and animals have certain physiological and developmental tolerances to particular combinations of temperature and precipitation within which they can survive and reproduce. These tolerances set limits to the range of environments that can be occupied. Thus, climate not only provides for the basic foundation for food webs, it also operates as a major determinant of where species can and cannot live.

Biologists have usually studied influences of climate in terms of mean values (often monthly), largely because that is the form in which high-quality data are available, rather than because of its specific biological relevance. While many biological patterns do correlate well with mean climatological values, mechanistically, the stronger drivers are likely to be cli-

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matic extremes, and thus we need to understand processes at this level to predict the impacts of future climatic trends, including global warming.

Why do extreme events drive many natural biological dynamics? Consider the ecological limits to a species' distribution. Species can potentially occur where a suitable climatological envelope coincides with the suite of resources they need to survive. Local adaptation can expand this envelope; for example, populations at the northern edge of a species' range are commonly more cold-tolerant and populations at the southern edge of the range more heat tolerant compared to interior populations. This fundamental, or possible, distribution is then molded by biotic interactions, such as predation and competition or gene flow from interior populations to produce the (frequently smaller) realized, or actual, distribution.

The suitable climatological envelope is determined by basic physiological requirements as well as length of the growing season. For plants this includes freeze, drought and heat tolerances and time available to successfully reproduce. For animals, time available to complete reproduction or enter the next life-history stage is also important, but additionally, they usually need to maintain a certain body temperature. This is true whether the animal is warm or cold-blooded, for body temperature influences crucial survival and reproductive activity such as predator avoidance, feeding, digestion, dispersal, flight, mating, and maturation of eggs. A species often becomes less abundant (fewer individuals or populations) near the limit of its range. For some species, this range limit represents the limit of some primary resource; for example, spruce distribution limits the spruce budworm. But for many species, the location of the range limit is due to a species experiencing increasingly harsh climatological conditions, leading to fewer and smaller populations, until some absolute physiological threshold is reached and survival is impossible. These limits are species-specific, e. g., temperatures that are harsh to one species may be suitable to another.

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The Zone of Tolerance

The air temperature range within which an animal can successfully compensate to keep its internal temperature constant is called the "zone of tolerance." When conditions are regularly outside the zone of tolerance of the active life-history stages, behavioral or life-history adjustments can allow survival and extend the range into more marginal conditions. There are four broad classes of compensating strategies:

1) Hardy life stage: A particular life stage of a species has a wider zone of tolerance than other stages (*e. g.*, seeds of annuals, eggs of some insect species) and is essentially unaffected by harsh conditions.
2) Hibernation/diapause/dormancy: During harsh seasons, individuals decrease metabolic demands thereby avoiding the need to feed or move about in unsuitable conditions (*e. g.*, maple trees dropping leaves, marmots hibernating, butterfly caterpillars entering diapause).
3) Migrations: Individuals move to more benign environments (*e. g.*, gray whales and New World warblers moving south during the Northern Hemisphere winter).
4) Daily behavioral adjustments: Behavioral mechanisms have been developed by some species that allow them to conserve energy or avoid the most extreme temperatures during harsh seasons (*e. g.*, birds huddling as a flock in a snug roosting hole for warmth or desert

rodents and reptiles hiding under rocks and bushes at the height of the summer day and foraging at night).

These compensatory mechanisms have evolved for a certain severity and frequency of non-suitable climate. Except for migrators, the individuals are-living off of reserves for the duration of the harsh time period. An increase in the proportion of time, either hours per day or days per year, in which the climatic environment is "out-of-bounds," or occurrence of climatic events so severe that these mechanisms fail, could result in loss of these marginal populations.

Catastrophic (Discrete) Versus Diffuse Events

Extreme climatic events can last for a few minutes, hours, or days, throughout a season, or over many years. We can fit extreme climatic events into two broad categories based on their scale: discrete catastrophic events and diffuse events. Diffuse events are those that cause prolonged stress rather than a sudden heavy impact. They are typically subtle in their action, affecting individual growth and reproduction that eventually will be observed in population and community dynamics. Catastrophes are those events that are large enough to cause ecosystem-level disturbances, such as floods that cause landslides and complete disruption of stream bottoms, hurricanes and tornadoes that cause large tree-falls in mature forest, or hot wildfires resulting from an extremely wet year followed by a drought year (particularly in grassland/chaparral habitat). The resulting successional processes may drive the system for years after the catastrophe. Generally, the effects of either type of climatic extreme on natural systems lie not only in the immediate impact, but also shape the recovery process. Whether the system, once perturbed, recovers to its original state or evolves to a new composition depends on the strength and duration of the climatic event as well as on the inherent properties of the specific system.

Diffuse events often have major cascade effects on evolution and ecology, far beyond the directly impacted species.

Just as marginal populations are susceptible to climatic thresholds, likewise, there may be community-level thresholds. The past decade has seen a realization by ecologists of the importance of catastrophes, and thus a reaction against steady-state models. For instance, hurricanes are now viewed as potential agents for increasing tropical forest diversity through disturbance. Many types of extreme events, however, are predicted to become more frequent and intense with climate change. If disturbance is essential to ecosystem health, is there also a point beyond which irreparable damage is done? Rapid, strong recoveries have followed two recent catastrophes in large, natural systems: the massive Yellowstone Park fire and the Mt. St. Helens volcanic eruption. However, natural ecosystems are becoming increasingly confined to small parks and major disturbance events are increasingly likely to result in such intense local damage that the system is unable to recover.

The diffuse events, which have more subtle effects than catastrophes on the success of individuals, are more likely to affect a greater proportion of wild plant and animal life. These events often have major cascade effects on evolution and ecology, far beyond the directly impacted species. This cascade effect has been shown to go beyond natural systems to impact human ecology. A recent example of this is the effect of heavy precipitation in the 1990s in the southwestern U. S. desert. Over several years, high precipitation events were

correlated with subsequent lush vegetative growth in this region, which in turn is correlated with population booms of a rodent that feeds on seeds from these plants. Unfortunately, this wild rodent carries the hanta virus that is transmittable to humans and frequently results in death. At normal population densities, the rodent doesn't come into contact with human settlements and so transmission of the disease is low. During these flood-induced population booms, however, over-crowding results in massive dispersal of the rodents into human settlements, with attendant human health impacts.

Even more subtle extremes — runs of several days of unusual weather for the season — have major impacts. For example, the probability of wildfires is strongly connected to several weeks in which afternoon temperatures are above 30°C with relative humidity below 50%. Higher variability of climate itself causes problems in wild populations. For instance, a week of unseasonably warm temperatures in the middle of winter (a "false Spring") is often sufficient to cause native plants and animals to break winter dormancy. Once dormancy is broken, the individual is in a much more fragile state and a return to more normal temperatures can result in death. The effects of more fine-scale climate extremes are less well studied in biological systems, but could become more important than catastrophic events in a future with global warming.

A week of unseasonably warm temperatures in the middle of winter (a "false Spring") is often sufficient to cause native plants and animals to break winter dormancy, placing individuals in a fragile state.

Data and Analyses Needs

To study the impacts of these debilitating extreme events on natural systems, biologists need a bevy of climatic analyses on ecological time and spatial scales. Raw climatic data, increasingly available through websites, has often not been tested for inhomogeneity (non-natural climatic signals such as those stemming from human error, changes in instrumentation or urbanization) and as such, they are often not particularly useful to biologists. Ideally, population biologists would collaborate with climatologists to obtain climate analyses specific to the biological system in question, but there are clear limits on the numbers of such studies possible via that route.

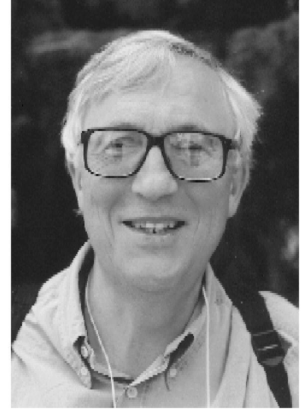
A more practical approach is to inform climatologists of the needs of biologists to ensure analytical outputs will be produced that can be referenced by biological researchers. This would not necessarily mean more complex analyses. For instance, including analyses of variability as well as mean trends would be simple yet enormously more useful for application to biological studies. Because the active part of the life-cycle of many organisms occurs in only a portion of the year, seasonal and monthly trends in temperature and precipitation are important. On an even finer scale, absolute numbers of extreme days in a month/season are useful indices. Further, the number of extreme days occurring in sequential runs merits attention. Finally, these analyses need to be conducted on a regional scale to match the scale of biological studies as well as to match real ecological divisions (*e. g.*, the Sierra Nevada mountains, the Mojave desert, the Great Plains states).

Coupling of these more detailed climatological analyses to biological processes will help tease apart the relative impacts of specific facets of a complex climatic regime on wild populations. As those mechanisms become better understood, mathematical models will be free to abandon yearly and monthly means in favor of more sophisticated suites of climatic

variables. Ecological and evolutionary theories, such as those concerning physiological energetics, population dynamics, community structure and ultimately management plans, are likely to gain descriptive and predictive power by having a better fit between the climatic and biological variables incorporated into the models.

Ideally, population biologists would collaborate with climatologists to obtain climate analyses specific to the biological system in question.

Terry Root discusses ecological impacts of climate extremes with Pasha Groisman and Natasha Andronova.



Why is the Global Warming Proceeding Much Slower than Expected?

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SESSION 2

The reduction of stratospheric ozone not only cools the lower stratosphere but also the troposphere, in particular the upper and middle part, leading to a significant reduction of the greenhouse warming.

Upper air observations from radiosondes and microwave satellite instruments do not indicate any global warming during the last 19 years, contrary to surface measurements where a warming trend is being found. This result is somewhat difficult to reconcile, since climate model experiments indicate the reverse of this, namely that upper tropospheric air should be warming faster than the surface. To help understand this difficulty, we have undertaken some specific experiments to study the effect on climate due to the decrease in stratospheric ozone and the 1991 Mt. Pinatubo eruption. The associated forcing was added to the forcing from greenhouse gases, sulfate aerosols (direct and indirect effects) and tropospheric ozone. Then we undertook an ensemble study in order to explore the natural variability of an advanced climate model exposed to such a forcing over 19 years.

The results show that the reduction of stratospheric ozone not only cools the lower stratosphere but also the troposphere, in particular the upper and middle part. In the upper troposphere, the cooling from stratospheric ozone leads to a significant reduction of the greenhouse warming. The stratospheric aerosols from Mt. Pinatubo generate a climate response (stratospheric warming and tropospheric cooling) in good agreement with microwave satellite measurements.

Finally, the analysis of a series of experiments with both stratospheric ozone and the Mt. Pinatubo effect shows considerable variability in its climate response, suggesting that an evolution having no warming in the period is as likely as another evolution showing a modest warming. However, based on the numerical experiments it is suggested that either the surface has warmed less than presently being claimed or the upper air data should show a slight warming trend instead of the cooling trend we now find.

Background

Several papers have recently addressed the problem of whether a climate warming caused by the ongoing increase in the atmospheric concentration of greenhouse gases is detectable or not. The general conclusion, as summarized by the latest IPCC report, is that there are indications that such a warming is underway. However, it appears that the warming is proceeding slower than expected and some data sets, such as the satellite Microwave Sounding Unit (MSU) data and radiosonde observations do not show any warming for the time-period 1979-1997 but rather a slight cooling. Other data sets, such as temperatures from surface weather stations and ocean ship and buoy data, show a warming trend of +0.15˚K/decade. The disagreement between on one hand the upper air and the surface observational

records and on the other hand between the model calculations (showing a distinct warming) and upper air observations (showing a slight cooling) has caused some consternation, and from some quarters the accusation has been raised that model results are unreliable in view of their inability to reproduce the temperature trend over the last two decades, the only time period with truly reliable global observations through the depth of the atmosphere.

It is not the intention in this paper to analyse in depth the apparent inconsistency between the surface temperature records and the microwave sounding data and radiosondes. Instead, we will describe our experiments which included the effect of ozone reduction in the stratosphere and the influence of the Mount Pinatubo eruption which we believe will contribute towards clarifying the issue raised above.

These experiments are part of a comprehensive climate change study carried out over the last two years at the Max Planck Institute for Meteorology in Hamburg. The main part of this investigation is being reported elsewhere (Roeckner *et al.*, 1999). It consists of three transient integrations with the ECHAM4/OPYC coupled model and an associated control integration considering the climate effect of greenhouse gases, sulfate aerosols and tropospheric ozone. These integrations were started in the year 1860 and were exposed to successively increased concentrations of greenhouse gases, tropospheric ozone and sulfate aerosols as determined from observed data. We will briefly summarize the results of these experiments, and those of simulations in which we replaced the representation of stratospheric ozone in the control experiment with the observed ozone values month by month for the years 1979-1997. We will also present results from the simulation of the Mount Pinatubo eruption, using actual data on geographical distribution of aerosols averaged monthly. Finally, we will summarize the results of a series of perturbation experiments investigating the combined effect of stratospheric ozone and the Mount Pinatubo eruption.

To consider the climate effect of greenhouse gases, sulfate aerosols and tropospheric ozone, three major transient climate change experiments have been carried out.

The Control Experiment

For these experiments we have used a coupled atmosphere-ocean GCM (Roeckner *et al.*, 1996). The atmospheric and land surface component of the coupled model is the 4th generation MPI model, ECHAM4. The ocean and sea ice is based on the OPYC model (Oberhuber 1993). The two model components are coupled through a mutual exchange of fluxes. Fluxes of momentum are unconstrained, while fluxes of heat and water vapor are flux adjusted, but only as annual averages. The purpose is to assure that the annual cycle of the model can interact freely with the coupled modes of the model.

Three major transient climate change experiments have been carried out, starting in the year 1860.

1) In "GHG," observed concentration of greenhouse gases and sulfate aerosols have been used until 1990 and thereafter changes according to the IPCC scenario IS92a. In this study, we concentrate only on the time evolution until present. Concentrations of the greenhouse gases CO_2, CH_4, and N_2O are prescribed as a function of time, as are a series of industrial gases including CFCs and HCFCs. The absorptive properties of each gas have been separately calculated (unlike most previous climate change studies where the minor greenhouse gases have been considered as proxy CO_2). Furthermore, we

have assured that the radiative forcing is practically identical to the narrow band calculations. This meant here an increase in the radiative forcing by some 10% compared to the actual broad band calculation in the radiation code of the model.

2) In "GSD" the greenhouse gases are treated as in GHG but with the additional incorporation of the tropospheric sulfur cycle as due to anthropogenic sources only. Natural biogenic and volcanic sulfur emissions are neglected, and the aerosol radiative forcing is generated through the anthropogenic part of the sulfur cycle only. Previous studies have mostly considered the effect of sulfate aerosols in a simplistic way by making use of an independent calculation of equilibrium distribution of sulfate aerosols, and then from this distribution modified the surface albedo correspondingly. In this study, we have integrated the full anthropogenic sulfur cycle in the atmospheric model including the actual geographical emission of SO_2, chemical transformation to sulfate, semi-Lagrangian transport of the sulfate aerosols, and finally the dry and wet disposition of sulfate particles from the atmosphere.
3) In the third simulation, "GSDIO," we have additionally included the indirect aerosol effect on cloud albedo as well as letting the tropospheric ozone distribution change as a result of the prescribed anthropogenic emission of precursor gases.

As can be expected, the long term warming is largest in experiment GHG and smallest in experiment GSDIO. Until 1980 or so, the fluctuations are more or less within the range of natural variability.

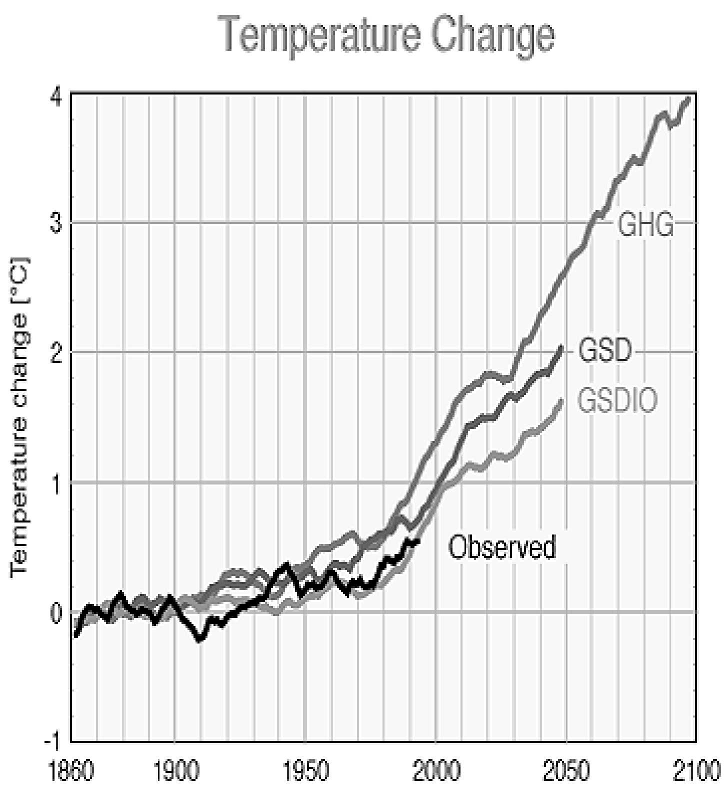

Figure 51
Decadal mean changes in the globally averaged surface temperature (K) in three different climate change experiments. The observed surface temperature is indicated by a heavy full line.

The global annual mean temperature change from the three experiments is shown in Figure 51. As can be expected, the long term warming is largest in experiment GHG and smallest in experiment GSDIO. Until 1980 or so, the fluctuations are more or less within the range of natural variability. The simulated temperature patterns undergo large low-frequency variations on a multi-decadal time scale in broad agreement with the estimated observed temperature pattern. In the model simulations there are pronounced ultra-low fluctuations at higher latitudes of the Southern Hemisphere; it is not possible to say whether these fluctuations are realistic or simply an artifact of the coupled model.

Since in this study we will discuss the evolution of the global temperature during the last two decades, it is important to note that there are considerable natural variations in the global temperature trend over such a short time-space. As can be seen from Figure 52, in the period 1979-97 the warming in experiment GSD is actually less than in experiment GSDIO, while in the longer perspective, Figure 51, the trend follows the radiative forcing broadly. This makes it virtually impossible to make any firm statements about the size of global warming from observational records from the two decades we are investigating here. Later, we will estimate the magnitude of the natural variability of the period 1979-97 by means of an ensemble type experiment. Finally, we also have the problem of the reliability of the observational records themselves (Hurrell and Trenberth, 1996 and 1998, Christy et al., 1998).

However, there are several additional factors which are important, namely, the climate effect of the stratospheric ozone reduction in the last decades and the influence of the 1991 Mt. Pinatubo eruption. Both of these occur in a period for which we have excellent coverage of global observations through the depth of the atmosphere mainly due to measurements from satellite observing systems, which were not available before 1979. Of particular interest here are observations from the MSU (Christy, 1995). In spite of some critical studies (Hurrell and Trenberth, 1997 and 1998), we find the evaluation by Christy and co-workers (Christy et al., 1998) convincing. There is also almost complete agreement between the MSU data and radiosonde observations. If both the upper air data and the surface data are correct, it is difficult to explain why the surface data and the SST data have a different trend than the data of the lower troposphere.

We have compiled the surface and the 500 mb temperature trend from the three experiments, GHG, GSD and GSDIO, with the observations from MSU, radiosondes and surface temperature data. The warming trend at 500 hPa is clearly positive in all three experiments, while both the radiosondes and the MSU T2LT have a slightly negative trend, indicating a minor global tropospheric cooling since 1979. The surface temperature warming trend of the model experiments with greenhouse gases is slightly smaller than at 500 hPa, the enhanced warming with height presumably caused by feedback through the moist adiabatic lapse rate. This is in disagreement with the observed data, where in fact we have an opposite relation: the surface is warming and the lower troposphere is cooling. Before we start to question the reliability of the surface or upper air data, we will analyze the results from the experiments incorporating the effect of the reduction of stratospheric ozone and the effect of the Mt. Pinatubo eruption.

The simulated temperature patterns undergo large low-frequency variations on a multi-decadal time scale in broad agreement with the estimated observed temperature pattern.

Stratospheric Ozone

In situ observations as well as satellite measurements, Stratospheric Aerosol and Gas Experiment (SAGE) and Total Ozone Mapping Spectrometer (TOMS) have clearly demonstrated the reduction in stratospheric ozone, in particular during the last two decades. The adjusted radiative forcing for the period 1979-94 suggests a negative overall value of 0.20-0.28 Wm^{-2}. The mechanism by which ozone depletion cools the surface is via reduction of longwave radiation to the surface due to cooling of the local atmospheric level. Of particular importance is the ozone reduction near the tropopause, where ozone absorption is still strong due to pressure broadening of the absorption bands. The specific vertical distribution of ozone is important and vertical re-distribution can change the result significantly. We have made use of a compiled data set produced month by month for the time period November 1978 to April 1993 and have linearized the trend for each month and for each latitude band and extended it for the whole period 1979-97. This data set thus includes the geographical variability, so the effect of the Antarctic ozone hole has been properly accounted for.

We have further undertaken two independent integrations for the period 1979-97 starting from slightly different initial states. The reference integration has been the experiment GSDIO and in the following we will consider this as the control experiment.

The mechanism by which ozone depletion cools the surface is via reduction of longwave radiation to the surface due to cooling of the local atmospheric level. Of particular importance is the ozone reduction near the tropopause.

Figure 53 shows the temperature trend as an average of two realizations of GSDIO + stratospheric ozone, experiment GSO, as well as the difference between this experiment and GSDIO. The two experiments are rather similar in the Southern Hemisphere and in the Tropics but differ substantially over the Northern Hemisphere. This is found both in the troposphere and in the stratosphere stressing the high level of internal dynamical variability not least in the stratosphere. This is again an example of the sampling problem, highlighting the importance of undertaking ensemble calculations for climate change studies.

The Mt. Pinatubo Eruption

The volcanic eruption of Mt. Pinatubo on the Philippine Island of Luzon on June 15-16, 1991 was one of the biggest in this century. It is estimated that 14-21 million tons of SO_2 were injected into the stratosphere. The volcanic cloud moved eastward by some 20 ms^{-1}, thus encircling the Earth in some three weeks, whereby SO_2 was converted into sulfate aerosols. In the first month, most of the aerosol mass was located in a band between 20°S and 30°N and then gradually the cloud spread to finally encircle the whole global stratosphere. Radiosonde observations as well as measurements from the MSU indicated a global stratospheric warming of about 2˚K. The observations also suggested a cooling of the lower global troposphere and the surface of the earth by about 0.5˚K. Whether the cooling of the troposphere was a consequence of the Mt. Pinatubo eruption is not so easy to determine, since there are considerable temperature variations caused for example by large scale air-sea interaction events such as El Niño. However, a cooling of the lower troposphere by about 0.5˚K is actually calculated by the coupled MPI-model.

There was also an extraordinarily high ozone reduction, which was detected in 1992 and 1993. At a later stage we intend to carry through an experiment with this coupled model incorporating the chemical processes occurring at the surface of the aerosol particles leading to an increase in active chlorine species and thus to ozone losses. In an experiment

described later in this paper, we used the observed ozone distribution, but only as a linear trend, so we have only partly incorporated the climate effect of this additional ozone destruction.

We carried through three specific experiments, two using GSDIO as the reference integration and a third using the GSDIO with stratospheric ozone as the reference integration. The volcanic aerosols (aerosol density, size distribution, chemical composition and three-dimensional distribution) were inserted during the period June 1991 to June 1993, but the integrations were continued until the end of 1997. As seen in Figure 54, all integrations clearly demonstrate a marked response of the Mt. Pinatubo eruption suggesting that the climate effect of a major volcanic eruption has a prolonged influence on the climate system due to the delayed influence of the oceans.

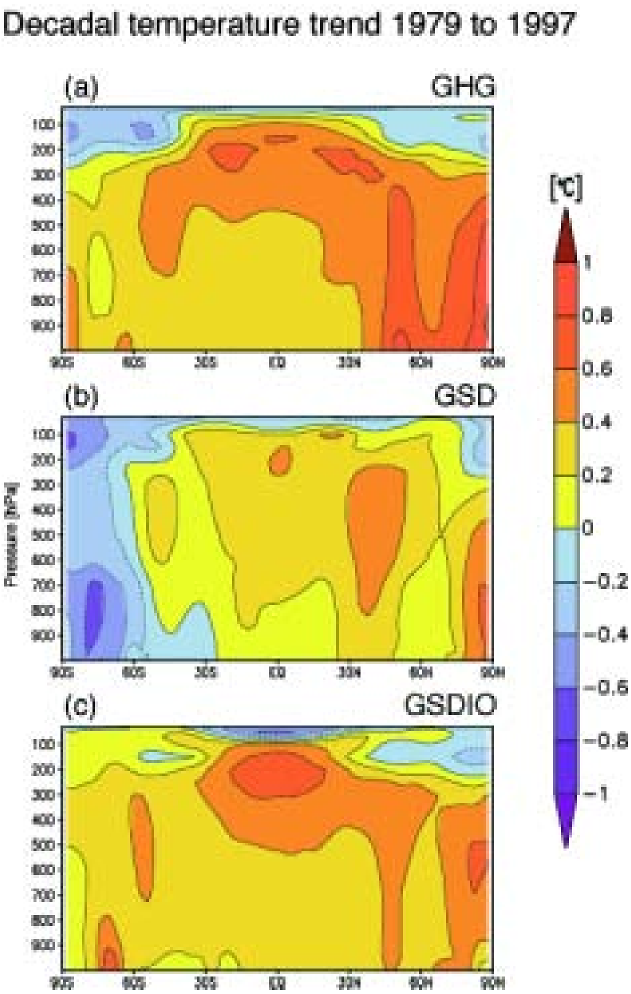

Figure 52
Zonally averaged cross sections of the decadal temperature trends for GHG (a), GSD (b) and GSDIO (c) valid for the period 1979-97. Note that due to internal stochastic variations the warming in the GSD is less than in GSDIO.

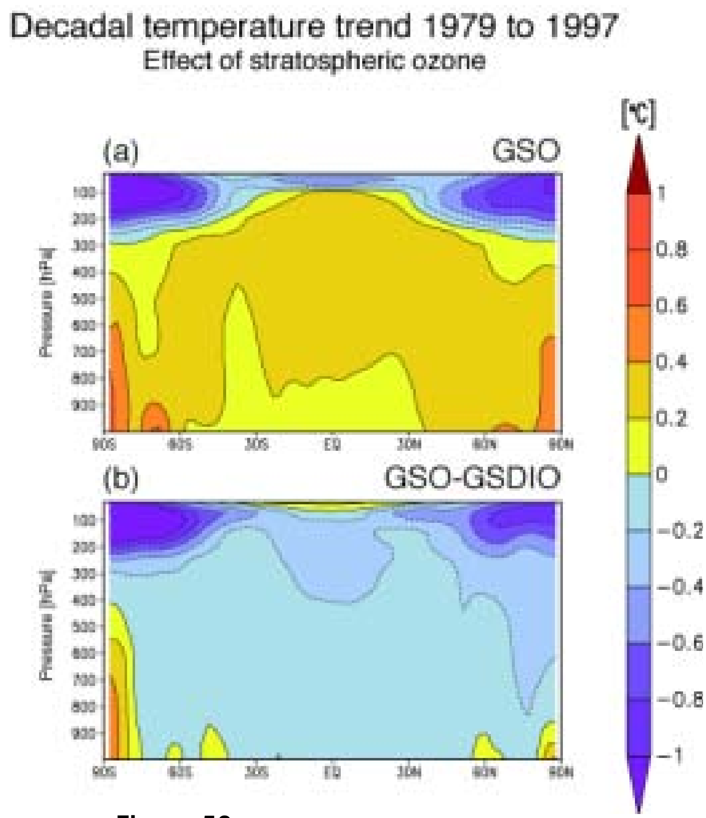

Figure 53
Zonally averaged cross sections of the decadal temperature trends for GSO (a) and the difference GSO-GSDIO for the period 1979-97. Mean of two realizations. Note the major cooling in the lower stratosphere at high latitudes.

Climate Change Evaluation

In order to obtain a preliminary estimate of an upper and lower bound of the temperature trend for the period we have combined the stratospheric ozone and the Pinatubo run into six separate realizations. A larger number of experiments would have been even better, but we restricted it for computational reasons. The six realizations have been composed from the three independent Pinatubo experiments and two independent stratospheric ozone runs, all integrations initialized in 1979 from the reference experiment GSDIO. Figure 54 shows the results from the different integrations compared to the observed MSU-data. The result of the experiments have been expressed in terms of equivalent MSU-data (Stendel and Bengtsson, 1997).

All integrations clearly demonstrate a marked response of the Mt. Pinatubo eruption suggesting that the climate effect of a major volcanic eruption has a prolonged influence on the climate system due to the delayed influence of the oceans.

SESSION 2

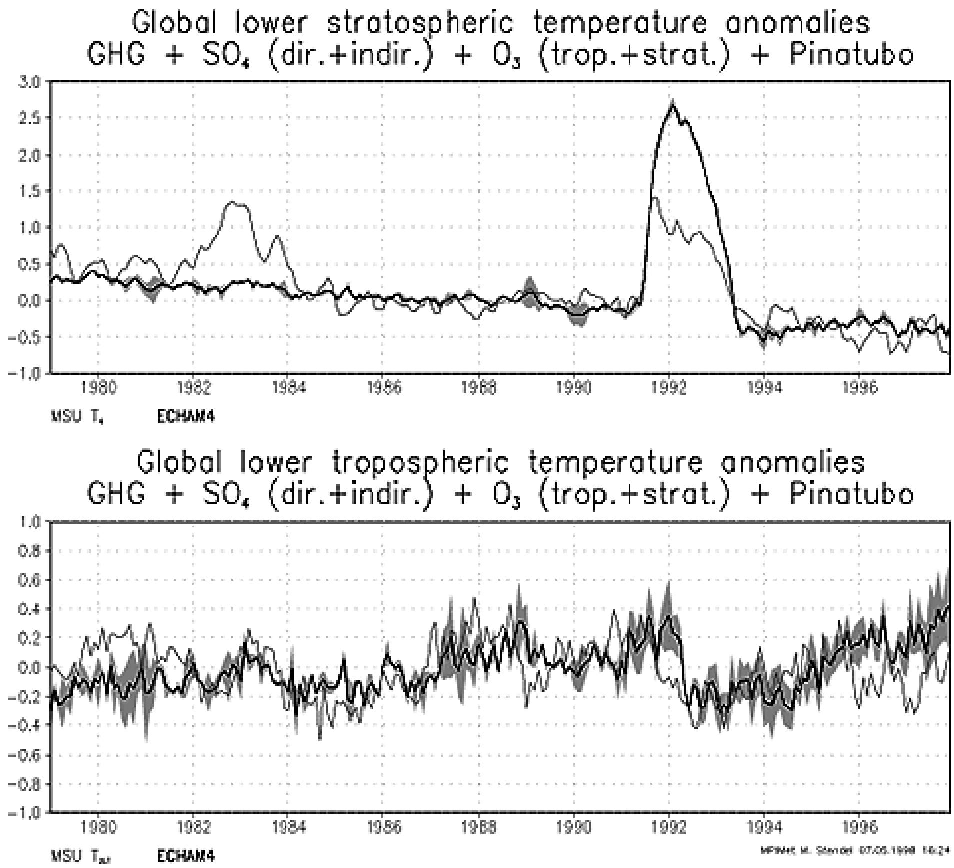

Figure 54

Observed MSU temperature, shown as dashed line, for channel 4 (top) for the period 1979-97 and the equivalent for the simulations with Mt. Pinatubo and stratospheric ozone. The mean value obtained from the six realizations is denoted by the solid line, whereas the shaded area represents this value plus and minus one standard deviation of the individual simulations, respectively. The same of channel 2LT (bottom). Note the steady response in the stratosphere and the large variability in the lower troposphere.

The simulated stratospheric warming is higher than the observed, with the differences related to an equatorial cooling associated with an easterly phase of the QBO (not yet possible to simulate by the model) and to the fact that stratospheric depletion of ozone due to the Mt. Pinatubo eruption was not incorporated. The tropospheric cooling is in broad agreement with the satellite observations, suggesting the Mt. Pinatubo eruption cooled the lower troposphere by some 0.5˚K. The standard deviation of the experiments is indicated by shading. Note the stable response of the Mt. Pinatubo eruption in the stratosphere.

It should be stressed that in this perturbation experiment we have only perturbed the initial state of the atmosphere and not that of the oceans. A realistic perturbation of the state of the ocean circulation is likely to further increase the variance within the ensemble. In the following we will show the mean of the six realizations as well as the cases with the largest and smallest warming trend, respectively.

Figure 55 shows three different zonally averaged cross sections of the different experiments including both Mt. Pinatubo and stratospheric ozone (mean, maximum and minimum trend, respectively). GHG and GSDIO have rather similar patterns but with a reduced warming in GSDIO. The largest warming occurs in the upper tropical troposphere and in the lower troposphere at high latitudes, particularly of the Northern Hemisphere. A cooling takes place in the stratosphere. The reduced stratospheric cooling in GSDIO is atypical and happens only during these two decades. The effect of reduced stratospheric ozone is to reduce the warming significantly, in particular in the stratosphere and the upper troposphere. The pattern changes similarly. The three cross-sections also incorporate the effect of the Mt. Pinatubo eruption. We show here the two extreme realizations. In the one with the minimum trend, the global trend is close to zero and the Northern Hemisphere is actually cooling.

Geographical patterns for the mean and the two extreme Mt. Pinatubo runs for 50 hPa, 500 hPa and the surface indicate that the stratospheric cooling at high latitudes of both hemispheres is strongly pronounced, and the warming trend in the Tropics is due to the Mt. Pinatubo eruption. At 500 hPa there are marked pattern variations between the different realizations due to the strong internal variability of the coupled system. The surface shows similar very strong variations between the different realizations, in particular at the surface. Over the Eurasian region (40°N-70°N; 10°W-135°E) the difference in decadal trend between the warmest and the coldest realization is as high as 0.88K. Assuming now that the real atmosphere behaves in a similar way, it is hardly possible to make any statements about climate warming or not by inspection of atmospheric global temperature records of this length and even less possible if we restrict the evaluation to certain regions.

In fact, we have good reasons to believe that the variability is even higher. We have here used GSDIO as a reference case. The period 1979-97 is a period of rapid warming in the GSDIO run; in fact it is significantly stronger than GSD, which over a longer time, in consistency with the stronger positive forcing, is warming more rapidly. If we only assume that GSDIO would behave in the same way as GSD over the period 1979-97 we might expect that this would also affect the stratospheric ozone and the Mt. Pinatubo run in a similar direction. In such a situation the stratospheric ozone and Mt. Pinatubo run could then have resulted in an overall cooling trend.

We have only perturbed the initial state of the atmosphere and not that of the oceans. A realistic perturbation of the state of the ocean circulation is likely to further increase the variance within the ensemble.

The stratospheric cooling at high latitudes of both hemispheres is strongly pronounced, and the warming trend in the Tropics is due to the Mt. Pinatubo eruption.

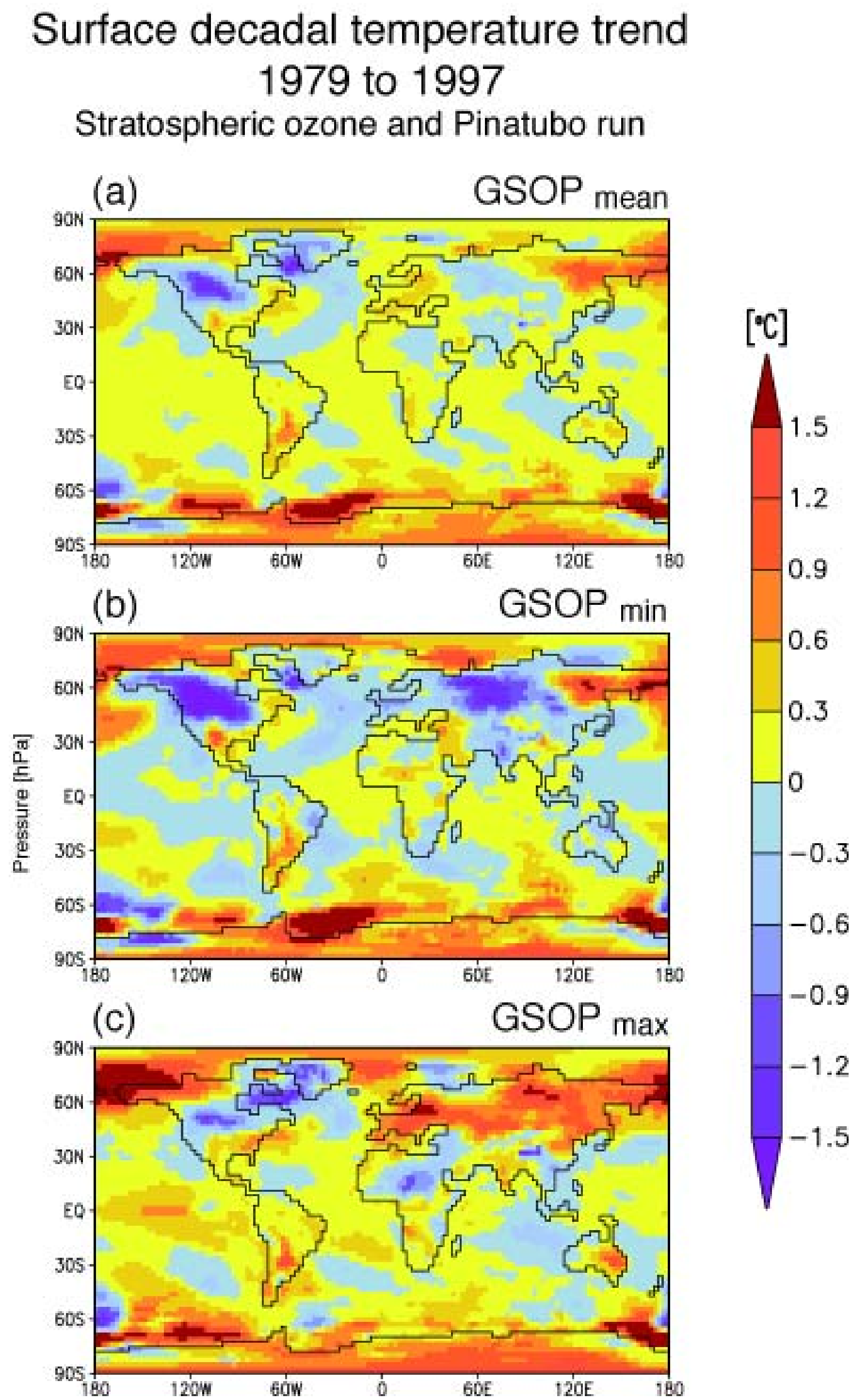

Figure 55
Zonally averaged cross sections of the decadal temperature trend 1979-97 for the averaged stratospheric ozone and Mt. Pinatubo run, GSOP (a), the same but for the case with minimum tropospheric warming (b) and the maximum tropospheric warming, respectively.

Conclusions

The purpose of these experiments was to clarify some of the perceived inconsistencies between global temperature observations over the last two decades and results from climate simulations with a high resolution, state-of-the-art global coupled model.

Firstly, it is a common result from available coupled GCMs that they show a considerable variability on timescales less than fifty years or so. This variability is due to internal dynamic processes and is in essence not possible to predict. Identical climate change integration differing only slightly in the initial state (well within the observational accuracy) generate patterns which after some time of integration are quite different from each other. A typical standard deviation in globally averaged decadal trends for a 20-year time-interval is of the order of 0.2-0.3K.

Does nature behave in a similar way? We have no reason to believe otherwise, although for some scientists and perhaps even more for non-scientists such a conclusion is hard to come by. It is not an uncommon attitude among investigators, in particular if inexperienced in non-linear dynamics, to ascribe any fluctuation to a specific forcing mechanism also when the forcing is modest and of a limited time duration (less than several decades). There is no evidence from studies of complex systems, like Earth's climate, that supports such a simplistic view. The history of meteorology and geophysics is filled with instructive evidence. The early but persistent and extensively documented explanations of the quasi-biennial fluctuation as the result of a sub-interval of the 11-year solar cycle is perhaps one of the most illuminating. Another example of a futile exercise is to search for tropospheric evidence of the 11-year solar cycle. With the size of the signal, the existence of internal atmospheric decadal modes and the limitations of the global observing system, such an exercise is hardly likely to lead to any useful results.

The climate effect of the ongoing reduction of stratospheric ozone is a clear cooling effect not only in the lower stratosphere but also in the troposphere.

Secondly, we have explored the climate effect of the ongoing reduction of stratospheric ozone. With the data-set we have used here, there is a clear cooling effect not only in the lower stratosphere but also in the troposphere. The result is strongly dependent on the vertical distribution of the ozone reduction, so more studies are required. It seems nevertheless that the stratospheric ozone change is highly important to include in climate change experiments. Due to the increased cooling by altitude it also reduces the strong upper air warming by the greenhouse gases in better agreement with observations.

Major volcanic eruptions such as Mt. Pinatubo also have a recognizable effect on climate. Although the direct forcing may be limited in duration to a few years at most, the effect on climate is longer due to the cooling of the oceans. In our experiments it appears that the effect of Mt. Pinatubo lasted for 5-7 years. The maximum tropospheric cooling amounts to about 0.5K, in agreement with previous estimates.

Based on six realizations we calculated the decadal global averaged surface temperature trend during 1979-97 to be between +0.19 to +0.04 K when we used experiment GSDIO as the reference. It is not unlikely that if we had instead used the GSD experiment, the values could well have been further reduced. In conclusion, therefore, it is certainly not unlikely that even a slight cooling could have taken place during 1979-97 in agreement with some

of the model integrations we have undertaken here. The inconsistency we have noted, though, is that the surface warming as assessed from surface synoptic records is in all likelihood on the warm side or alternatively the MSU-data and the radiosondes observations are on the cold side. To clarify which of the data sets are most reliable is the purpose of another study. The vertical gradient of the temperature trend in the model integrations is slightly reduced with height when we incorporate the effect of stratospheric ozone, but significantly less than for the observations, 0.02K compared to 0.19K per decade.

It must finally be stressed that the fact the no warming may have taken place during the last two decades can in no way be interpreted as evidence that there is no anthropogenic climate warming. In fact, we may expect a recovery of the stratospheric ozone during the beginning of next century, which will reduce or eliminate the compensatory cooling effect. Volcanic eruptions are not predictable, but their effect is limited in time. Perhaps the most difficult factors to consider are the aerosol effects, their scattering albedo or even more the indirect effect such as the interaction with cloud albedo and possible influence on cloud life-time.

The fact the no warming may have taken place during the last two decades can in no way be interpreted as evidence that there is no anthropogenic climate warming.

SESSION 2

Acknowledgement
The authors acknowledge the provision of ozone data from Dr. P. Fortuin, KNMI and the Mt. Pinatubo aerosol data from Dr. G. Stenchikov. The authors also wish to thank O. Esher, K. Niedl and N. Noreiks for technical assistance. The experiments were supported under the EU Contract No. ENV4-CT95-0099.

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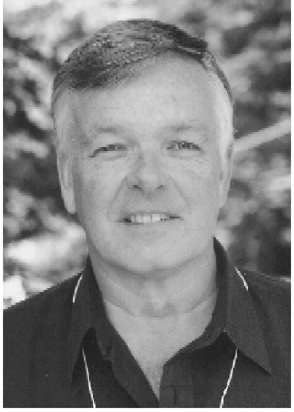
A recovery of the stratospheric ozone will reduce or eliminate the compensatory cooling effect.

Extremes Validation at the National Climatic Data Center



Michael J. Changery
National Climatic Data Center
Asheville, North Carolina

The National Climate Extremes Committee is chaired by a representative of the National Climatic Data Center (NCDC) in Asheville, North Carolina and extremes considered to be new national records validated by the Committee are provided to the NCDC Director for final approval.

The purpose of the National Climate Extremes Committee (NCEC) is to assess the scientific merit of extreme meteorological/climatological events and provide a recommendation to NOAA management regarding the validity of the measurement. The NCEC will also act to disseminate NOAA's recommendation of the event and coordinate media inquiries with the National Weather Service Public Affairs Office. The NCEC was established in 1997 following an investigation into a possible 24-hour snowfall record at Lake Montague, New York.

The purpose of the National Climate Extremes Committee (NCEC) is to assess the scientific merit of extreme meteorological/ climatological events.

In addition to the NCDC representative, the Committee members include representatives from the National Weather Service's Office of Meteorology and the American Association of State Climatologists (AASC). The AASC member is the current president of the organization. Discussions on the role of the Committee and its interaction with the state climatologist community is conducted annually at the annual meeting of the AASC.

The Federal Committee's mandate is restricted to national extreme values of the elements listed in Table 12. The Table provides previously accepted national extremes through 1997, along with the location and date of each occurrence. The Committee's mandate does not include the reevaluation of the existing extreme values listed. This list may be expanded as additional element extremes, such as greatest monthly rainfall/snowfall are developed. Some elements, such as hail size and short-duration rain rates, are frequently reported in the media. Because they are anecdotal and non-objective in nature, the Committee is not responsible for validating reports of this nature.

Extreme values which are not national in magnitude are validated using current procedures. Local daily/monthly/annual records at National Weather Service (NWS), Federal Aviation Administration and possibly military sites, are the responsibility of on-site personnel. State records for most listed elements are maintained at NCDC and new records will be validated via communication between NCDC, NWS, and the state climatologist for the state in question. If the state does not have an active state climatologist program, coordination will be with the Director of the Regional Climate Center (RCC) covering the state. NCDC will update the list of state records with any reports validated through this procedure.

Table 12
Currently Accepted U. S. Climate Extremes

Temperature (˚F)			
Maximum	134	July 10, 1913	Greenland Ranch, CA
Minimum	-80	Jan 23, 1971	Prospect Creek, AK
Max 24-hour temp. change	100	Jan 23-24, 1916	Browning, MT
Snow (inches)			
Maximum 24-hour	75.8	Apr 14-15, 1921	Silver Lake, CO
Max Seasonal (Jul-Jun)	1122	1971-1972	Paradise RS, WA
Max Snow Depth	451	Mar 11, 1911	Tamarack, CA
Rain (inches)			
Maximum 24-hour	43	Jul 25-26, 1979	Alvin, TX
Least Annual	0.00	1929	Death Valley, CA
Maximum Annual	704.83	1982	Kukui, HI
Longest dry period	767 days	Oct 3, 1912-Nov 8, 1914	Bagdad, CA
Wind (mph)			
Maximum Gust	231	Apr 12, 1934	Mt Washington, NH
Pressure (mb/in)			
Lowest	892.3/26.35	Sep 2, 1935	Matecumbe Key, FL
Highest	1078.6/31.85	Jan 31, 1989	Northway, AK

If, in the judgement of the NWS, a national extreme value warrants investigation, the NWS will assemble a team with the geographic and technical expertise required to determine the accuracy of the reported extreme.

- For national extremes reported from NWS sites, the measurement will be examined for compliance with established NWS guidelines and specifications. Specifically, the investigating team will assess observational procedures, instrument exposure and operation, along with reporting equipment maintenance and calibration. At a minimum, the investigating team will be composed of personnel from the site in question (for WSO sites) or the NWS Cooperative Program Manager for cooperative sites, instrument and observational procedures specialists from NWS Headquarters, and the state climatologist, or if necessary, a representative from the RCC covering the state in question. Additionally, the state climatologist or RCC representative from the state with the current national record will also be invited to participate as a member of the investigating team.

- For national extremes reported from local meso-networks, the team should include the mesonet service technician, head of the mesonet, the local NWS Cooperative Program Manager, instrument and observational procedures specialists from NWS Headquarters, and state climatologists or RCC representatives covering the state with the current record and potential record.

The investigating team will assess observational procedures, instrument exposure and operation, along with reporting equipment maintenance and calibration.

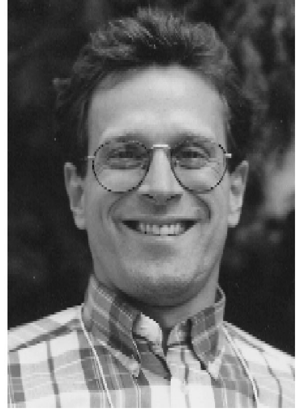
- For national extremes reported from a military location, the Office of the Federal Coordinator for Meteorological Services will coordinate communication between the military instrument and observational specialists, NWS personnel and the requisite state climatologist/RCC representatives.

During the course of the investigation of a national extreme, the NCEC will maintain liaison with the investigating team and will provide a coordinated response to the NWS Public Affairs Office for the handling of media inquiries of the status of the investigation and validity of the report. Once the investigating team has finalized its report, the NCEC will provide a recommendation on the event to the Director of the NCDC, who will in turn determine the declaration. The NCEC will then report on the decision.

In the summer of 1998, extreme temperatures at Death Valley (129˚F) re-opened the controversy of the validity of the U. S. record of 134˚F.

Since the Committee was established, the NCEC has reported on the validity of prospective wind and temperature records. During the passage of Typhoon Paka over Guam in December 1997, a military reporting site reported a peak wind gust of 238 mph. Analysis of site damage and the reporting instrument led to a decision to discount the reading. The lack of damage at the site, the reported gust factor of 125% and the discovery that the wind instrument was a hot wire anemometer, which reports erroneously when impacted by heavy precipitation, were reasons documented to discount the report. In the summer of 1998, extreme temperatures at Death Valley (129˚F) re-opened the controversy of the validity of the U. S. record of 134˚F. Given the Committee's mandate to not reevaluate historical extremes, it was decided that the 129˚F reading was the highest verifiable maximum temperature in the U. S. since the national record occurred.

Mike Changery makes a point to Camille Parmesan and Dave Easterling.



Evaluation of Insurance Data and What It Can Tell Us About Climate Extremes

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A climatological assessment of a series of exceptionally severe and damaging storms during 1991-94 was pursued to put these events and their frequency and intensity into a temporal perspective. Many reasons have been offered for the high frequency of severe weather events and extensive economic losses including an increased sensitivity of the nation's population to storm damage (LeComte, 1993), unusual weather conditions (Rodenhuis, 1996), and a possible shift to a stormier climate, a condition claimed by some scientists to be related to the human-altered greenhouse effect on global climate (Leggett, 1993, Karl et al., 1996). Review of past climatological studies of severe weather conditions revealed that it was difficult to select data to be analyzed for such comparative purposes. One, it is difficult to obtain measures of the meteorological intensity of severe weather events based on available physical measurements such as patterns of high winds, distribution of damaging hail, or the areal extent of heavy rainfall amounts. This situation makes a physically-based comparison of severe weather events distributed over many decades impossible. Furthermore, an important aspect of severe weather events is that they are defined in two ways: 1) by their type (flood, hail, hurricane, tornado, etc.) and physical characteristics (wind, pressure, rainfall rate, etc.), and 2) by the amount of damage they cause (Changnon and Changnon, 1996).

The weather insurance industry has developed and used two sets of data that integrate the event types with the losses they caused while adjusting individual storm losses to changing socioeconomic conditions.

For these reasons, the recent severe weather events were assessed according to the damage they caused. Incorporation of storm damages brings another uncertainty about past events into the picture: the ever-changing sensitivity of society to storms. In time, the cost of repairs changes, the dollar value shifts, the population density in a location varies, and structural methods and codes for buildings are altered. Realizing state-by-state reporting of such events varied significantly, *Storm Data* could not provide comparable numbers for spatial or temporal analysis. Fortunately, the weather insurance industry has developed and used two sets of data that integrate the event types with the losses they caused (Changnon and Changnon, 1990). Importantly, the industry had developed processes for adjusting individual storm losses to changing socioeconomic conditions.

One record provides the adjusted property losses created by "catastrophic" events (Property Claims Services, 1995) so that losses from weather events in 1951 could be compared to those in 1991. Three adjustment factors were used on each storm event, and their magnitude depended on storm date, storm type, and the geographical location of the damage. The first adjustment factor employed integrated changes with time of property values and cost of repairs. The second adjustment factor addressed the relative growth in the size of the

fixed property market in the area(s) affected by the storm between the year of its occurrence and today's. The third adjustment factor represented an estimate of the relative changes in the share of the total property market that was insured against weather perils between the year of catastrophe occurrence and that of the current year.

The other record, which dates back to 1948, is an index of the amount of crop-hail loss per year (NCIS, 1995). The crop-hail insurance industry has collected by state (and each crop) information about annual liability, premiums and losses. The insurance data have been adjusted for temporal changing liability (coverage), dollar values, and other factors by using the "loss cost." The annual loss cost value for a state is determined by dividing the annual losses ($) by the annual liability ($), and multiplying the resultant value by 100.

Investigation of Catastrophes

All analyses were based on adjusted event values and two levels of catastrophe values were selected for study: a) those causing between $35 million and $100 million in losses (320 catastrophes), and b) those causing >$100 million in losses (189 catastrophes). This choice allowed examination of the temporal differences between small/moderate catastrophes and the large events.

The number of catastrophes producing $35-$100 million in losses remained fairly level at four from 1950 through 1974 before increasing to a peak of 13 for the 1990-1994 period.

A. Catastrophes Producing $35 Million to $100 Million in Losses

Five-year average annual values appear in Figure 56, showing that the number remained fairly level at four from 1950 through 1974 before increasing to a peak of 13 events, as the average number for the 1990-1994 period. The five-year average annual losses caused by these 320 catastrophes (Figure 56) showed a similar trend, increasing from less than $200 million in the early years to $743 million during 1990-1994. Importantly, the trends of both catastrophes' frequency and amount of loss are similar to the trend in the nation's population, especially after 1974, as shown in Figure 57. Changes in the U. S. population over the 45-year period were found to explain 82% of the variations in the average number of these catastrophes and 78% of the average losses (Changnon and Changnon, 1998). Interestingly, the annual intensity (annual losses/annual number of catastrophes) of such storms actually remained level or decreased during the 1949-1994 period indicating that the storms in this category were not becoming more extreme and that the increase in frequency and losses was related to either more storms or to increased societal vulnerability (risk) to these types of weather events over time.

B. Catastrophes Producing >$100 Million in Losses

The five-year average annual frequency of these storms show a high-low-high, or U-shaped distribution (Figure 58), much different than that found for the small/moderate catastrophe (Figure 56). Since an earlier study found a relationship between catastrophes >$100 million and the national frequency of extratropical cyclones (Changnon and Changnon, 1992), the curve based on these events was plotted in Figure 58. The two curves are somewhat similar except the increases in large catastrophes since 1974 may also be related to population increases or shifts of the population to more vulnerable locations such as coastlines, urban centers, and the West. The temporal trend of annual losses for these catastrophes (Figure 59) is essentially unchanging and marked by five one-year peaks. These peaks are associated with the occurrence of major U. S. hurricane strikes. Furthermore, when the intensity of large catastrophes is considered, the annual cost per event decreased from its peak in the early 1950s and has remained nearly level since the mid-1970s.

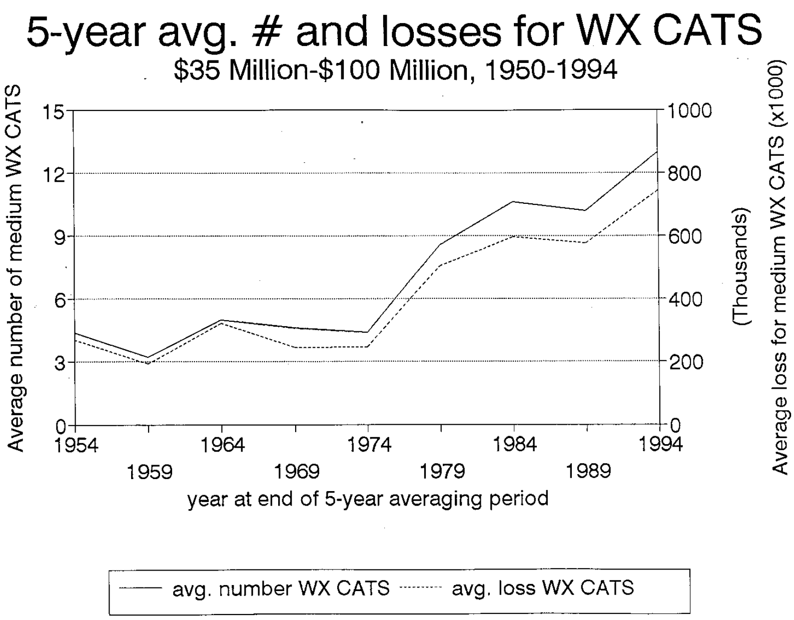

Figure 56
The average annual values of the frequency of and losses from adjusted catastrophes (WX CATS) producing $35 million to $100 million in losses, based on five-year totals, for 1950-1994 (Changnon and Changnon, 1998).

The trends of both catastrophes' frequency and amount of loss are similar to the trend in the nation's population, especially after 1974.

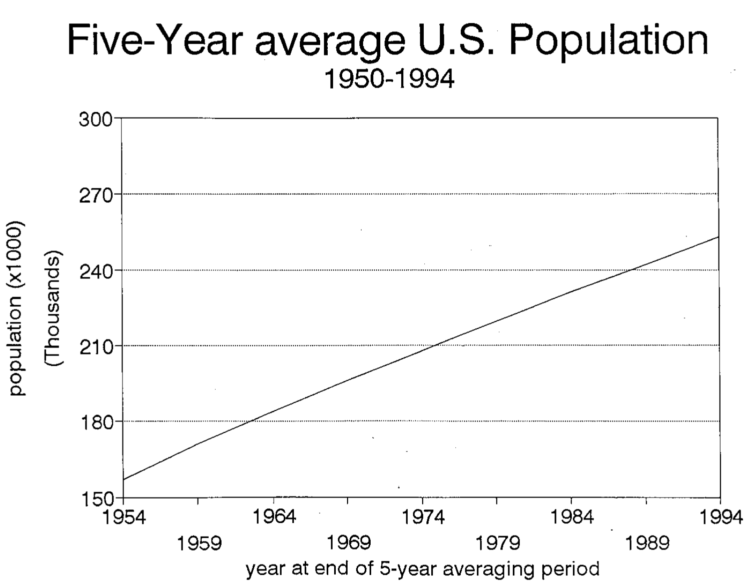

Figure 57
The five-year average U. S. population for the period 1950-1994 (Changnon and Changnon, 1998).

The peaks in Figure 59 are associated with the occurrence of major U. S. hurricane strikes.

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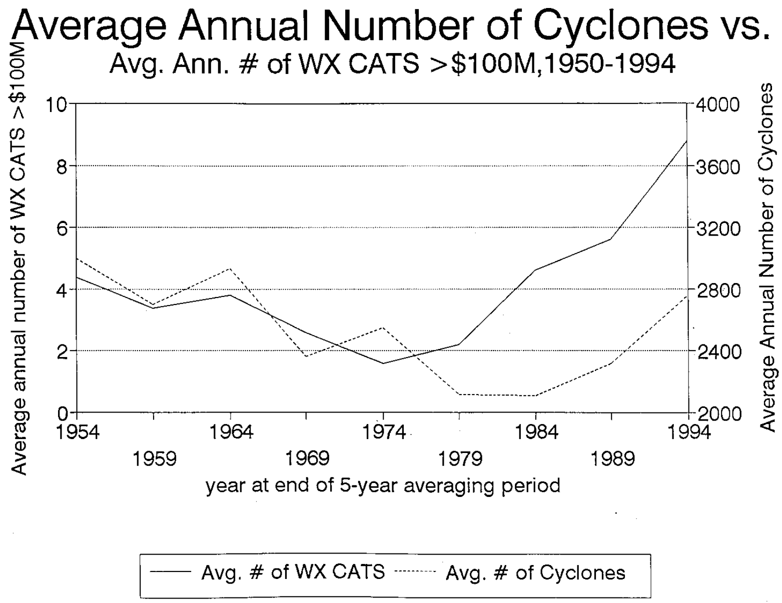

Figure 58

The average annual number of adjusted catastrophes (WX CATS) causing >$100 million in losses and annual number of North American cyclones for 1950-1994, based on five-year totals (Changnon and Changnon, 1998).

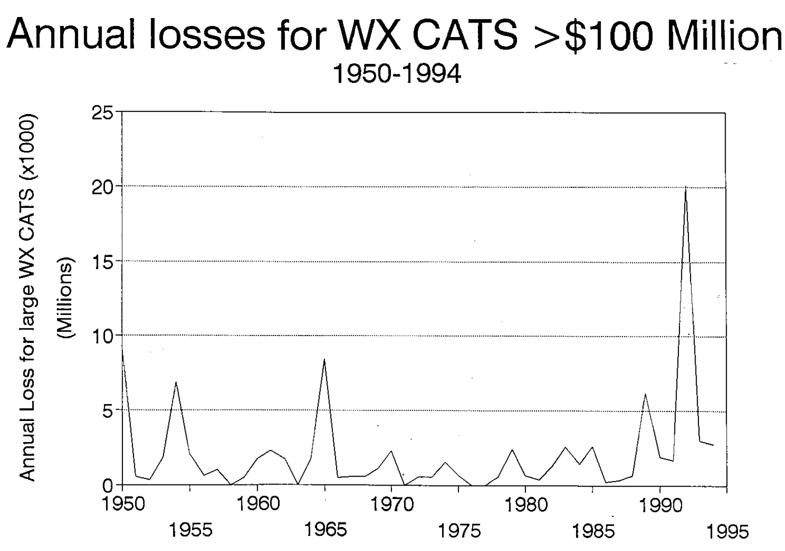

Figure 59

The annual losses from adjusted catastrophes (WX CATS) causing >$100 million in losses, 1950-1994 (Changnon and Changnon, 1998).

Investigation of Crop-Hail Losses

The assessment of the national crop-hail loss distribution during the 1948-1994 period revealed that the loss costs in 1992-1994 were relatively high (Figure 60). Past three-year periods of high loss costs similar to those in 1992-1994 were assessed. The average loss cost value for that period was $3.25, however the average loss cost was $3.27 for 1954-1956 and $3.38 for 1961-1963. Thus, the recent high loss costs have been exceeded twice in prior periods since 1948. Comparison of the annual frequency of cyclones in the eastern U. S. and the national loss costs for 1948-1994 yielded a correlation coefficient of +0.62, indicating that the cyclone frequency explained 38% of the variability in the loss costs. This weak correlation could reflect the fact that hail is generally produced from small-scale weather systems (thunderstorms), those that may or may not occur in conjunction with larger scale extratropical cyclones.

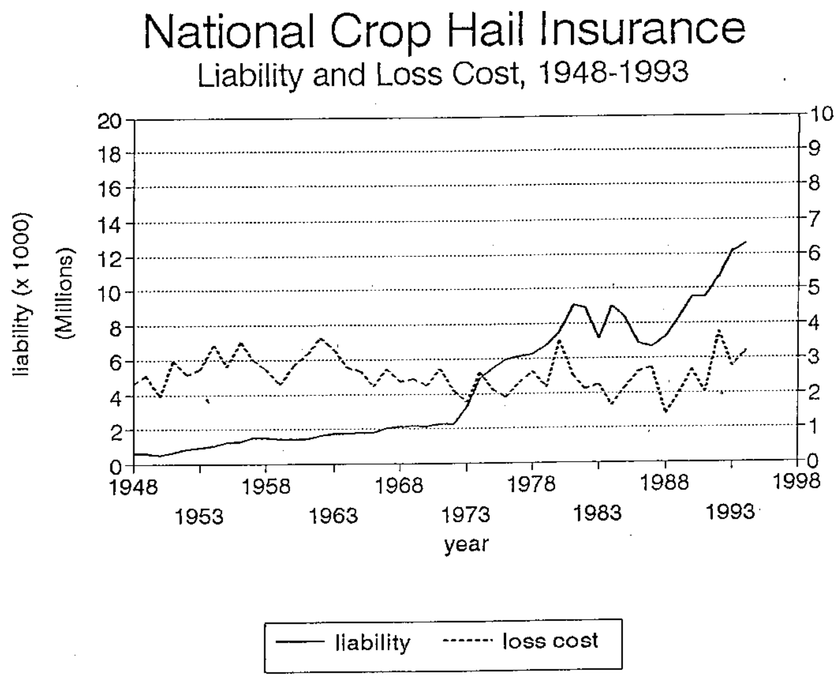

Figure 60
Annual values of loss cost and liability for the U. S., 1948-1994 (Changnon and Changnon, 1996).

Conclusions

Insurance-derived measures of property and crop losses due to severe storms during 1949-1994 were assessed for use in studies of temporal variability and change. The results showed that the 1991-1994 catastrophes (property losses) ranked high in number and amount of loss. However, storm intensity (losses divided by number of storms) was found to be higher in the 1950s.

The results showed that the 1991-1994 catastrophes (property losses) ranked high in number and amount of loss. However, storm intensity (losses divided by number of storms) was found to be higher in the 1950s.

The frequency of losses related to small/moderate ($35 million to $100 million) catastrophes increased throughout the 1949-1994 period and were related to the steady increase of population. This result suggested that the adjustments applied to these smaller catastrophes

by the insurance industry did not adequately normalize for population increases or societal vulnerability (risk) to these storms.

The 189 catastrophes causing >$100 million in losses had high frequency values in 1991-1994, however the number of these large catastrophes was also relatively high in the 1950s. Crop-hail losses in the U. S., as measured by the "loss cost," were high during 1992-1994, but were higher in the 1950s and early 1960s. The losses related to the >$100 million catastrophes exhibited a flat time distribution with isolated peaks in those years when major hurricanes struck the U. S. coastline (1950, 1954, 1965, 1989, and 1992). Although the large catastrophes appeared to be somewhat related to changes in extratropical cyclone frequency over North America there was still concern about whether the adjustments used by the insurance industry were adequate.

The 189 catastrophes causing >$100 million in losses had high frequency values in 1991-1994, however the number of these large catastrophes was also relatively high in the 1950s.

The annual adjusted loss values for all 509 catastrophes (>$35 million) were divided by annual U. S. population values (interpolated from decadal census data) to normalize for population changes (Figure 61). This graph shows that other than the five years with major U. S. hurricane strikes, the annual loss per person in this country has remained below $20. These results reveal that the insurance adjusted technique employed did not adequately allow for the influence of other factors including non-fixed property, design standards, building codes (and their enforcement), and personal goods (Changnon and Changnon, 1998). Nevertheless, when normalized for population changes, this data set can be used as an indication of potential changes in losses related to damaging storms.

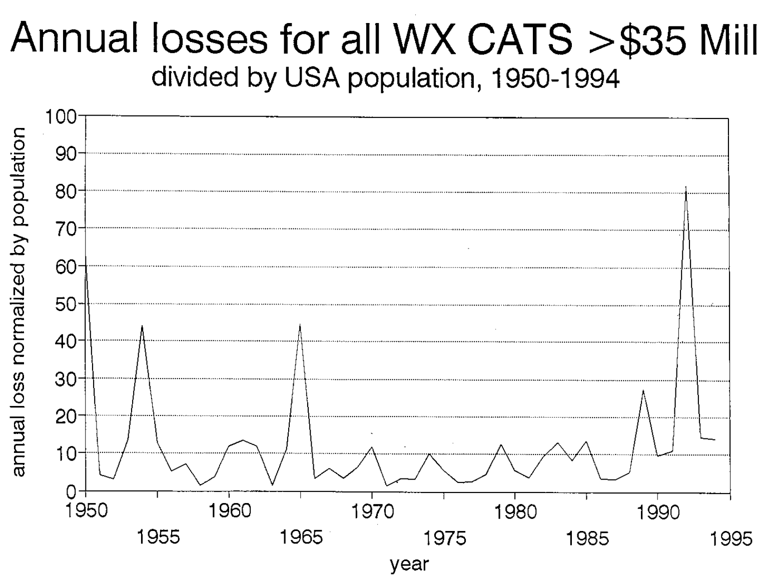

Figure 61
Normalization of adjusted catastrophe losses to U. S. population, based on annual values of loss due to adjusted catastrophes (WX CATS) causing >$35 million in losses divided by U. S. population for 1950-1994 (values in dollars per person) (Changnon and Changnon, 1998).

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Acknowledgments
The author would like to acknowledge that this research was supported by UCAR and NSF awards. Special thanks go to Stanley Changnon, Don Friedman, and Tom Zacharias who provided the adjusted property loss values and crop-hail data.

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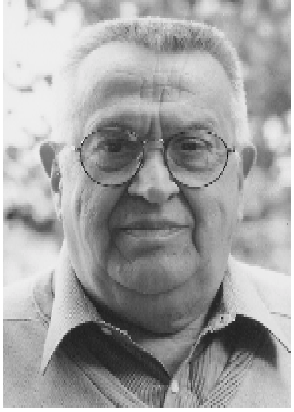

Key Issues Relating to the Impacts of Weather and Climate Extremes

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Involvement in numerous studies of how weather and climate conditions impact physical systems and society, accomplished over the last 45 years, is the basis for most comments herein. These observations are meant to provide an overview of the key issues that face the definition, study, and interpretation of impacts from weather/climate extremes, including data and methodological problems, as well as to identify future research needs. These are offered as a series of eight premises.

Most individuals and decision makers in business and government react to climate fluctuations from knowledge of their impacts rather than from knowledge of their physical effects.

Premise 1: Knowledge and definition of weather and climate impacts are critically important.

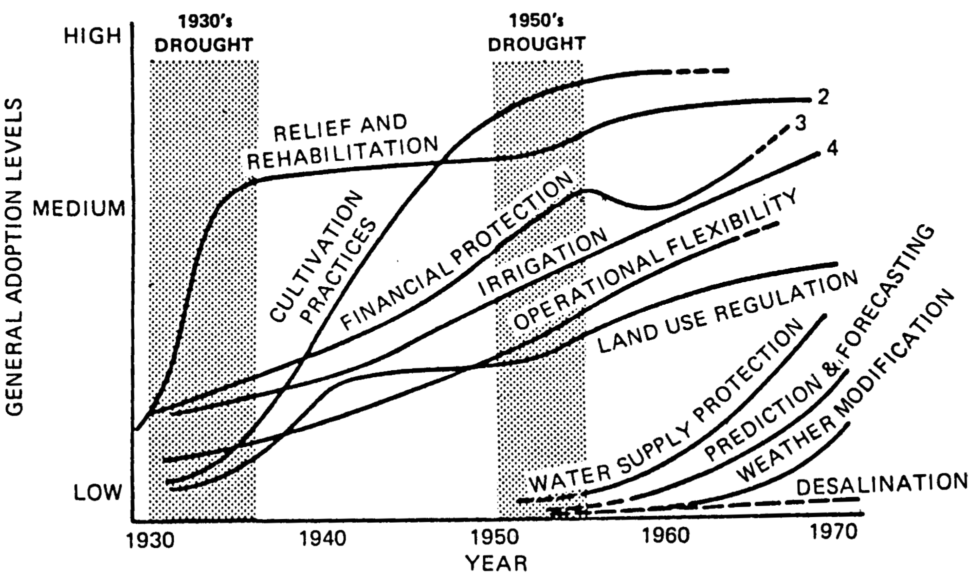
Society everywhere in the 1990s is facing the possibility of a changing climate due to global warming, and society is now more climate sensitized as a result of the recent unusual weather conditions in much of the world. The predictions of monthly and seasonal weather outcomes due to events like El Niño 1997-98, and the scientific estimates of future climates of the 21st century generated by global climate models, have created interest and wide concern as to their effects on environmental systems and impacts on society. Unfortunately, too little definitive research has been accomplished to quantitatively define most of the real and potential impacts of the shorter-term El Niño-type variations or the longer-term potential shifts in climate. Most of what we know about effects is qualitative. Knowledgeable reactions to and decisions regarding these types of climate conditions, either short-term or long-term, require better information than currently exists on the physical effects as well as the socio-economic impacts. Furthermore, most individuals and decision makers in business and government react to climate fluctuations from knowledge of their impacts rather than from knowledge of their physical effects. Demonstrating that a 24% decrease in heating costs occurred in the Midwest during 1997-98 is more influential information than showing that it was a 2.6˚C warmer winter. Hence, the definition of weather and climate impacts is critically important if one seeks to influence the decision process at all levels (Changnon, 1996a).

Premise 2: There is a continuum from weather extremes in physical effects, to societal impacts, to societal responses, to delayed impacts, and to ensuing adjustments.

Adequate understanding of the effects of weather and climate extremes requires a realization that weather extremes launch a complex series of impacts and responses that occur from hours to years after the event. A weather extreme such as a heavy, prolonged rainfall creates physical effects such as flooding and soil erosion, followed by a myriad of impacts to society, some good and many harmful. These impacts bring about a variety of responses to recover from the damaging impacts. Some impacts and responses, such as rebuilding

structures or relocating a town after a flood continue for months and years after the event, and some adjustments require many years.

Figure 63 illustrates the sequences of outcomes, as measured in a comprehensive study of impacts, of changed weather in the St. Louis urban and downwind rural areas (Changnon et al., 1981). The altered climate conditions create several direct physical effects in the environment, followed by a wide variety of complex socio-economic impacts and responses. Figure 62 shows, in schematic fashion, the types of long-time responses and adjustments that followed the severe droughts of the 1930s and 1950s, revealing that it took years and even decades for various actions to develop locally, regionally and nationally.



1) Very rough approximation of relative levels of adoption.
2) Institutional arrangements for R&R (not payments).
3) Shape of curve generalized from number of acres insured and amounts of loans in the U. S. (dip in the 1950s reflects lower adoption of insurance at that time).
4) Based on total irrigated acres in the U. S.

Figure 62
A schematic showing the rate of adoption of various responses to the major droughts of the 1930s and 1950s, as accomplished at the local, regional and national scales

Premise 3: All weather conditions cause impacts, and weather extremes are events that cause unexpected losses in a region and sensitivities to a given weather/climatological events vary regionally and seasonally.
There is often confusion and uncertainty over the definition of weather extremes, particularly if assessment begins with some measure of the deviations of weather conditions from the norm. This approach is often fraught with vagueness and unreality for decision makers and non-atmospheric scientists. For example, definition of a 2-inch daily rainfall as an extreme weather event may be climatologically correct for the range of rainfall classes at many U. S.

Altered climate conditions create several direct physical effects in the environment, followed by a wide variety of complex socio-economic impacts and responses.

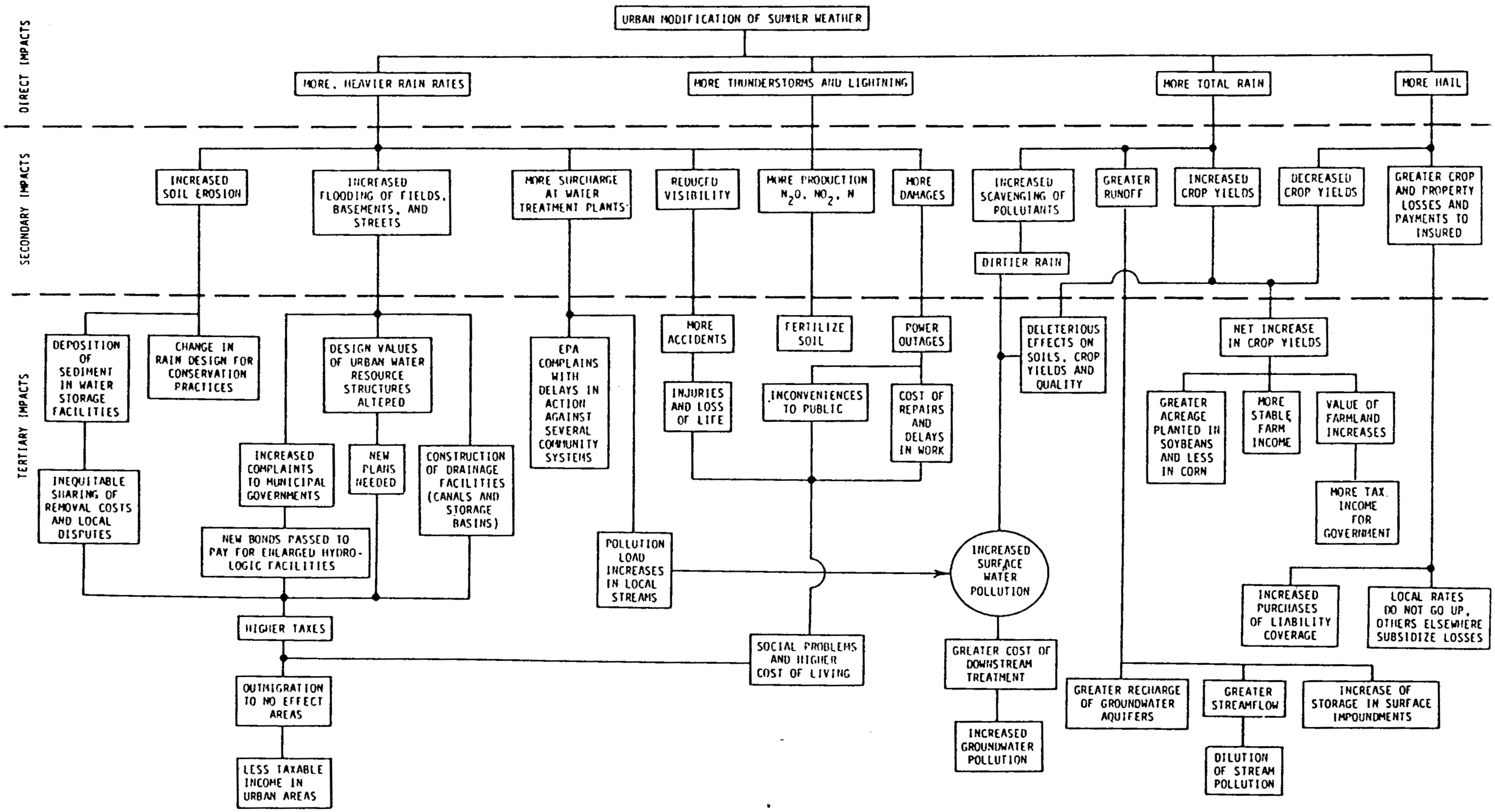


Figure 63
The sequence of impacts and responses created by the urban-induced changes to summer rainfall and storms at St. Louis.
(Changnon et al., 1981). The physical changes in the weather conditions are labeled the "direct impacts." The "secondary impacts" are those in the physical-environmental systems caused by the altered weather conditions, and the "tertiary impacts" include time-spatially delayed impacts and societal responses to the impacts.

locations, but a 2-inch rainfall during the Midwestern growing season is both an expected and desired event that aids crop production. A 2-inch all-day rain in winter in most parts of the U. S. has some measurable effect on streamflow but is not considered an extreme event by hydrologists.

There are two other major lessons about extremes and their definition. First, is the recognition that hour-by-hour and day-by-day weather conditions cause a variety of physical and human impacts, without any extremes occurring. Second, extremes become defined as unusual events in a given region based on the area's unique physical setting and its own set of sectoral sensitivities to the weather. For example, a run of days with maximum temperatures above 95˚F in Texas seldom creates power interruptions or human health problems, but the same run of temperatures in the north central U. S., such as in Chicago, produces numerous deaths and great problems in the provision of electrical power (Changnon, et al., 1996). The key point that is not well understood by many is that extremes and their impacts vary seasonally and regionally, and that these sensitivities *define* extremes.

Premise 4: The weather sensitivities of many physical systems and some societal activities are well-known but are changing with time.

Research in a variety of disciplines over the last 100 years has defined, for most areas of the U. S., the elements of the physical-environmental system that are influenced by weather. This includes weather effects on runoff, streamflow and crop production. Although many of the weather effects of extreme events are well known qualitatively, many have not been defined quantitatively. Fortunately, recent studies of major U. S. weather extremes such as the drought of 1998 (Riebsame et al., 1991), the flood of 1993 (Changnon, 1996b), and Hurricane Andrew (Pielke, 1995) have provided a spectrum of quantitative information about the variety of socio-economic impacts and responses to these events. In summary, the sectoral impacts and locations of impacts that can occur from the variety of weather/climate extremes are well known but in many instances have not been measured well quantitatively. Furthermore, these impacts vary regionally, as explained in the prior premise, and must be defined at the regional level for each extreme. In addition, changes in technology and society alter the impacts of extremes. A hot-dry summer in Iowa in 1997 has different effects on corn yields than the same conditions had in 1947 or 1913.

The sectoral impacts and locations of impacts that can occur from the variety of weather/climate extremes are well known but in many instances have not been measured well quantitatively. Furthermore, these impacts vary regionally.

Premise 5: Precise definition of physical effects and socio-economic impacts of weather extremes is impossible, and all data contains errors that must be assessed.

Those attempting to understand and interpret the effects of weather/climate extremes must be aware that all data defining physical effects and socio-economic impacts of weather is less than precise and contains errors. Similarly, as has been well demonstrated, all types of weather and climate data contain errors due to a variety of problems associated with weather instrumentation, places of measurement, continuity of data collection, and changes in measurements.

Awareness of the imprecision involved in defining impacts is important in interpreting the accuracy of numbers that measure the effects of extremes. For example, stream gauges that measure river flows can create errors that many do not appreciate. The massive 1993 flood

in the Midwest led to efforts to calculate losses and costs during the flood and for several years afterwards. These estimates of total loss ranged from a low of $12 billion, to $15 billion, and eventually to a measured loss of $19.2 billion (Changnon, 1996b). This illustrates that depending on how thoroughly an extreme event is studied and how good the data used to assess the impacts are, the amount of estimated loss can vary considerably.

Premise 6: Quality analyses of the physical effects and socio-economic impacts of weather extremes are difficult and require multi-disciplinary talents.
The nature of the wide spectrum of complex impacts from a weather extreme, such as a drought or a hurricane, necessitates careful study. Impacts occur in various parts of the environment including the hydrologic cycle, and spread through many elements of society and many sectors of the economy, leading to complex responses including insurance or government actions (Figures 62 and 63). Thus, adequate studies of the impacts of extremes require skills from a variety of disciplines. Unfortunately, impact assessment has too often been attempted with inadequate efforts. Adequate funding and long-term commitments by U. S. federal agencies to build multi-disciplinary teams to accomplish sustained, quality studies of weather impacts has not occurred.

Environmental and economic losses due to weather extremes will continue to escalate because societal vulnerability is growing.

Premise 7: Those responding to weather/climate extremes vary according to the type of extreme.
Weather and climate extremes bring about a variety of responses to adjust and restore societal activities and to recover from damage to physical systems. Interestingly, those who pay for restoration vary according to the types of hazards. For example, major droughts such as that of 1988-1989, create major impacts in the hydrological and biospheric systems and in farming communities. The greatest costs to respond to severe droughts typically fall to the individual, to the federal-state governments (crop relief), and to local-state entities to adjust or create water supply systems (Riebsame *et al.*, 1991). Conversely, major storms such as Hurricane Andrew result in enormous expenditures by the private insurance sector which pays for the excessive damages to property such as buildings and vehicles. In major floods such as that of 1993, federal expenditures for restoration are excessive, whereas private sector insurance costs are relatively small (Changnon, 1996b). Thus, building a database of the costs of weather/climate extremes, including both the direct losses and the costs of restoration, must rely on data involving the insurance industry, the local-state-federal government, and a sampling of impacted individuals who suffer losses they must cover alone. Such a database is needed to provide better estimates of the impacts of weather extremes.

Premise 8: Environmental and economic losses due to weather extremes will continue to escalate because societal vulnerability is growing.
There is concern that fluctuations in the climate, including greater variability or more weather extremes, will produce large stresses on physical systems and society. Regardless of global warming, we can safely predict that the climate of the next 50 years in any part of the U. S. will be different than that of the last 50 years. Differences in precipitation between the first and second halves of the 20th century in large parts of the U. S. (Karl and Knight, 1998) are sufficiently large to affect designs of certain hydrologic systems and to enhance water supplies.

Recent weather losses have raised concern that they are the result of a shifting climate (Changnon *et al.*, 1997). Several studies of the impacts of recent extremes have found that the recent increases in losses (and costs) are largely a result of on-going shifts in societal factors (Pielke, 1997; Changnon, 1998). Key U. S. societal factors that have been identified as shifting and causing increased vulnerability to extremes include:

- growth of population causing a greater density of targets for damage;
- demographic changes reflecting that many are moving into harms way, both into ever-larger urban areas and along vulnerable coasts;
- increasing wealth in property and possessions leading to greater loss per event;
- construction practices that are not adequate to provide safeguards from storm damages, such as inadequate roofing against hail;
- technological shifts that have increased vulnerability to events such as power or communication outages.

Predicting the future directions of technology and society well into the 21st century is a much greater challenge than predicting the climate of that century and thus makes the estimation/prediction of impacts of future weather extremes, say in the year 2050, practically impossible. Unfortunately, current directions of society indicate increased vulnerability to extremes and this makes it safe to predict ever-increasing losses and costs from weather extremes into the next few decades.

Conclusions

From many years of personal research and study of the literature, I have learned some lessons that relate to the issue of weather and climate extremes and their effects.

- First, *detecting* the effects of a changed climate on physical and socio-economic systems influenced by human actions is very difficult. It requires skilled and careful comprehensive analyses, but it is as important to society as any form of atmospheric research.
- Second, future changes in society are the key to adaptation to a shifting climate in the 21st century, and societal and technological changes of the future are very difficult or impossible to predict with any certainty. This makes estimation of the effects of shifts in future weather and climate extremes pure speculation.
- Third, if the past is a prologue to the future, societal and environmental adaptation to future climatic shifts seems the most likely outcome, at least for the next several decades (Changnon, 1995). The major difficulties in adapting to these weather/climate shifts will come from changes in the variability and extremes of the climate, not from shifts in the mean or average condition.
- Fourth, greater certainty than exists in 1998 over future changes of climate and its magnitude and structure, such as extremes, could lead to major savings in infrastructure replacement and designs of weather-sensitive systems to gain greater future flexibility. Greater flexibility in weather-sensitive sectors is good business, particularly recognizing that the climate of the next 50 to 100 years will be different, regardless of cause, than the climate of the past 50 to 100 years. Hopefully, greater understanding amongst decision makers will lead to the planning and expenditures to attain greater flexibility in weather sensitive systems.

Future changes in society are the key to adaptation to a shifting climate in the 21st century, and societal and technological changes of the future are very difficult or impossible to predict with any certainty.

Greater flexibility in weather-sensitive sectors is good business, particularly recognizing that the climate of the next 50 to 100 years will be different, regardless of cause, than the climate of the past 50 to 100 years.

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Variations and Trends in Extreme Events in the U. S.

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Climate model estimates of the potential impact of increases in radiatively-active trace gases in the atmosphere suggest that the globe will likely experience a warming of 1-4˚C, with attendant increases in the vigor of the hydrologic cycle over the next century. Much of this change will likely manifest itself in the form of increases in the frequency of extreme events. In this paper observed trends in global and U. S. temperature and precipitation will be discussed, both in terms of mean values and extreme temperature and precipitation events. Recent work indicates that 10 of the last 15 years (through 1997) have been the warmest global temperatures on record, and that North America has experienced a precipitation increase of 10-20% over the 20th century. In the U. S. and other countries much of the precipitation increase can be attributed to increases in heavy and extreme precipitation events. These increases have occurred in both single-day and multi-day precipitation events. Lastly, the U. S. has experienced a significant decline in the number of days where the temperature dips below freezing, particularly in the spring. This appears to be related to recently observed decreases in spring snow cover over North America.

The 1997-1998 period produced a number of climate extremes in the United States. The strong El Niño event of 1997-1998 resulted in an exceptionally wet Southeastern U. S. which then turned into an extensive drought. For example, northeastern Florida experienced the wettest November-March period ever, which was followed by the driest April-June period on record which resulted in extensive forest fire activity. The Intergovernmental Panel on Climate Change report (IPCC 1995) suggests that if the climate changes due to human influences, more extremes of temperature and precipitation can be expected. In this paper trends in climate extremes in the U. S. are examined. In particular, trends in both single-day and multi-day precipitation events, along with trends in certain types of temperature extremes for the U. S. are examined.

Precipitation Extremes

During recent years there have been a notable number of catastrophic flooding events. In 1993 the upper Mississippi river experienced exceptional flooding due to a period of persistent heavy precipitation. The autumn of 1996 produced heavy flooding in New England, in the winter of 1997 there was heavy flooding in California, and in the spring of 1997 heavy flooding occurred in the Red River valley of North Dakota, and along the Ohio river. Precipitation in the U. S. has been shown to be increasing over the 20th century (Groisman and Easterling 1994a). One question is: how much of this increase is due to increases in heavy precipitation events?

North America has experienced a precipitation increase of 10-20% over the 20th century. In the U. S. and other countries much of the precipitation increase can be attributed to increases in heavy and extreme precipitation.

Recent work by Karl *et al.* (1996) and Karl and Knight (1998) have examined changes in 24-hour precipitation totals in the U. S. over the 20th century. Karl *et al.* (1996) found that there has been an increase in the proportion of area in the U. S. affected by heavy precipitation events (defined as 24-hour totals greater than 50 mm). Karl and Knight (1998) examined changes in total annual precipitation as a function of changes in total number of rain days per year, and changes in the number of heavier precipitation events (defined as those events falling in the highest percentile). They found that changes in total precipitation in the U. S. was a result of both changes in the total number of days with precipitation (+ 6 days per year), and increases in the intensity of precipitation events. Large flooding events are usually the result of heavy precipitation over a number of days. Kunkel, et al. (1998) looked at trends in 7-day precipitation totals for the U. S.. They found increases in events that exceeded the one-year recurrence threshold for most areas of the U. S. Seasonally, the boreal autumn had the largest increases, and only winter had statistically insignificant increases.

Temperature Extremes

There have been relatively few studies of temperature extremes in the U. S. DeGaetano (1996) found increases in the number of days where the temperature exceeded 32˚C (90˚F) in the northeastern U. S. Furthermore, Cooter and LeDuc (1994) found that the frost-free season in the northeastern U. S. has increased by almost 11 days since 1950. Easterling (1998) found that the number of days where the temperature falls below freezing has decreased in the U. S. by almost 2 days per decade since the late 1940s. The largest decreases are found in the northern Great Plains and Great Lakes regions. Seasonally the largest decreases occur in the spring in these same two areas, which is likely related to the decrease of spring-time snow cover documented in Groisman, et al. (1994b).

The U. S. has experienced a significant decline in the number of days where the temperature dips below freezing, particularly in the spring.

SESSION 2

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Dave Easterling, Mike Changery and Camille Parmesan discuss data needs for assessing ecological impacts of climate extremes.

During recent years there have been a notable number of catastrophic flooding events. How much of this increase is due to increases in heavy precipitation events?

Looking Ahead: How Can We Efficiently Interrogate the Climate Models?

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The basic message of this talk is that regional climate change assessment of monsoon and tropical cyclone variability should combine information on all of the dominant processes affecting the system variability using spatial and temporal scales well simulated by the global climate models (GCMs) used for these sensitivity analyses.

Extreme rainfall events directly attributable to tropical cyclone passage occur with a 5-7 year return period over much of the northeast U. S.

Regional assessments of tropical cyclone activity have typically regarded the present domain of influence of tropical cyclones as being restricted almost exclusively to the global tropics. We show (Figure 64) that extreme rainfall events (monthly rain ≥ 200% of the long-term mean) directly attributable to tropical cyclone passage occur with a 5-7 year return period over much of the northeast U. S. Return periods reduce to as little as 2.5 years when the definition of an extreme rain event is chosen as ≥ 150% of the long-term mean. Obviously, even in the present climate, tropical cyclones contribute regularly to extreme weather events in the northeast U. S. They also have a minor effect on western Europe (not shown). These analyses suggest that the complete life cycle of tropical cyclones, and not simply their early, tropical phase, should be considered when assessing their impacts on the climate system.

The relationship between SST>28˚C and tropical cyclogenesis (Gray 1975) has been cited as evidence that tropical cyclones are likely to form further poleward and at higher frequencies in a warmer climate than presently (*e. g.*, IPCC 1990). However, the causal link between this threshold (SST>28˚C) and tropical cyclone activity in the resent climate has never been clearly drawn. We propose that this threshold corresponds to the region of the globe in which deep tropical convection is observed to extend through the depth of the troposphere. Graham and Barnett (1987) demonstrate that environmental factors other than ocean temperature (SST) govern the depth of tropical convection for SST>28˚C, but that it is only in this SST regime in the present climate that the deepest convective towers are observed. Acceptance of this hypothesis as the likely explanation of the link between SST and tropical cyclone activity in the present climate immediately suggests a number of secondary links to tropical cyclone activity. It also raises a number of questions on the robustness of this numerical threshold in other climate regimes.

We first address the likelihood that SST>28˚C will remain the numerical threshold for deep, tropical convective activity. Graham and Barnett (1987) plotted outgoing longwave radiation (OLR) against SST for the global tropics. We repeat this analysis for three GENESIS climate model simulations to explore if the 28˚C threshold is robust across differing climate regimes (Figure 65). Equilibrium simulations for (a) a control simulation; (b) 2xCO_2 equilib-

rium simulation; and (c) $4xCO_2$ were analyzed. Comparison of the control simulation with the observational study of Graham and Barnett (1987; not shown) reveals a realistic relationship between OLR and SST in the model control run. Comparison of the control simulation with the other climate realizations suggests that the threshold of SST > 28˚C in the present climate for deep convective clouds in the tropics may not be maintained in other climate regimes. This important result indicates that an understanding of the true nature of this threshold to tropical cyclogenesis is necessary to inferring likely tropical cyclone activity changes in differing climate regimes.

Mean Return Period (years): Doubling of Mean Monthly Rainfall from a Tropical Cyclone (1930-1996)

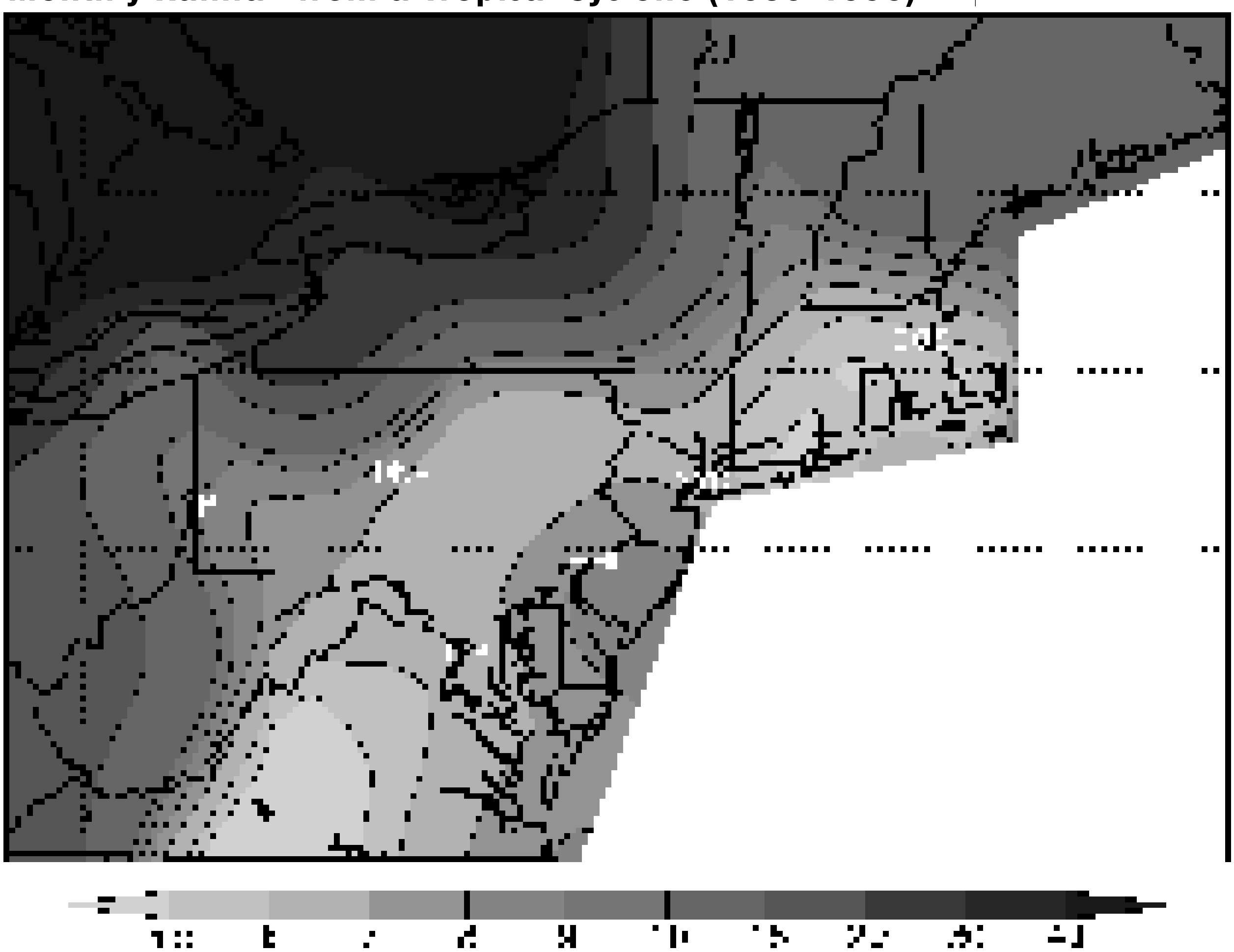


Figure 64

Return periods for extreme rainfall events (200% of normal) derived from monthly station data over the northeast USA for the period 1930-1996 inclusive. No Canadian stations are included. Events are only included in this climatology if the extreme rainfall was directly attributable to the passage of a tropical cyclone.

Requirements for tropical cyclogenesis are an ability to support deep convection and an incipient seed disturbance.

SESSION 2

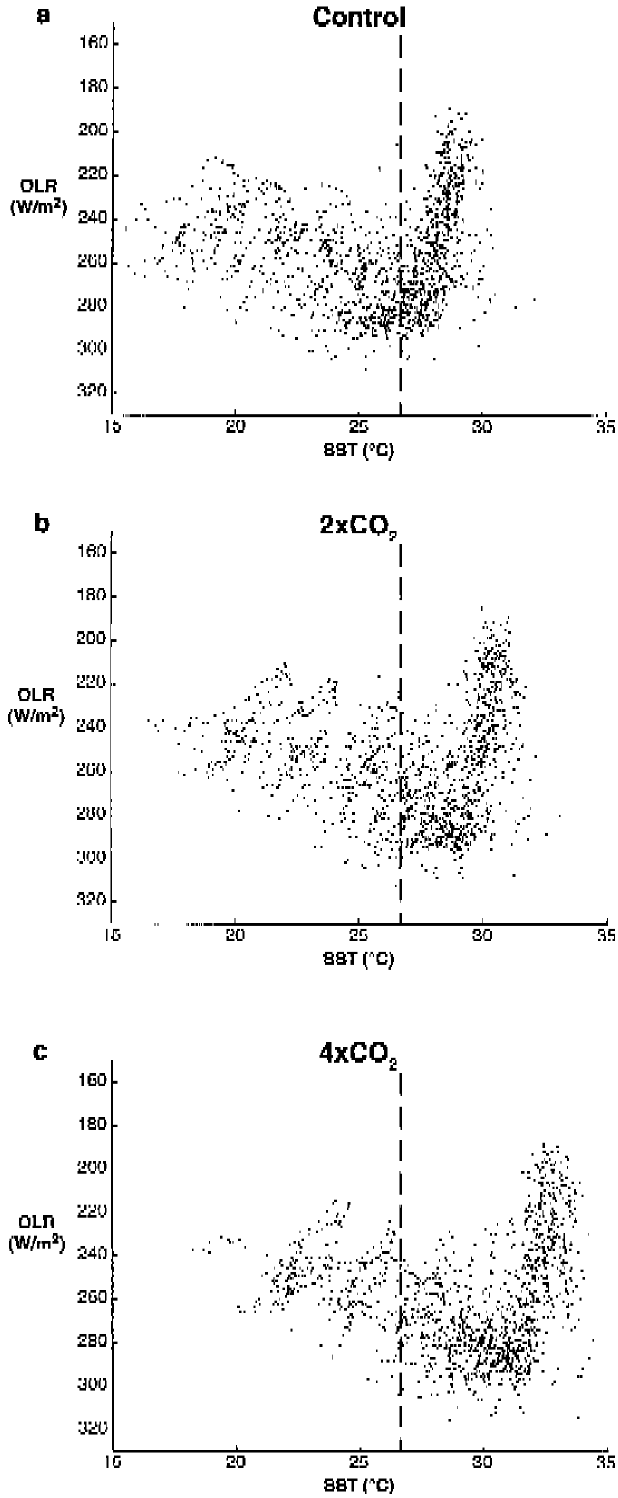


Figure 65
Relationship between sea surface temperature (SST) and outgoing longwave radiation (OLR) for GCM tropical convection in (a) control simulation; (b) 2xCO_2 equilibrium simulation; and (c) 4xCO_2 equilibrium simulation of the GENESIS climate model. Comparison of the control simulation with the observational study of Graham and Barnett (1987; not shown) reveals a realistic relationship between OLR and SST in the model control run.

We now consider a number of environmental factors that have been identified as important for tropical cyclogenesis. While many theories on tropical cyclogenesis exist, requirements for tropical cyclogenesis common to them all are: (a) an ability to support deep convection; and (b) an incipient seed disturbance. In most parts of the world, the conditions corresponding to the monsoon trough environment isolate for deep convection. Since the monsoon trough is a region of low-level cyclonic vorticity, it is also a favorable region for development of "seed" disturbances, with over 90% of tropical cyclogenesis cases in the Australian and western North Pacific Oceans being located in the monsoon trough. It is also the dominant genesis location for Indian Ocean tropical storms. In the Atlantic Ocean, easterly waves provide the seed disturbances for developing tropical cyclones in the vast majority of cases. Thus, successful simulation of tropical cyclogenesis suggests a need for adequate simulation of these seed systems. Concepts addressed here are illustrated for the month of February 1993. Tropical SST for February 1993 is plotted in Figure 66. SST>28°C is shaded and the locations of all tropical cyclone genesis events for this month are indicated by bulls eyes. Obviously, tropical cyclone genesis locations are restricted to this SST regime, although no tropical cyclones form in the near-equatorial region where the SST are actually maximum.

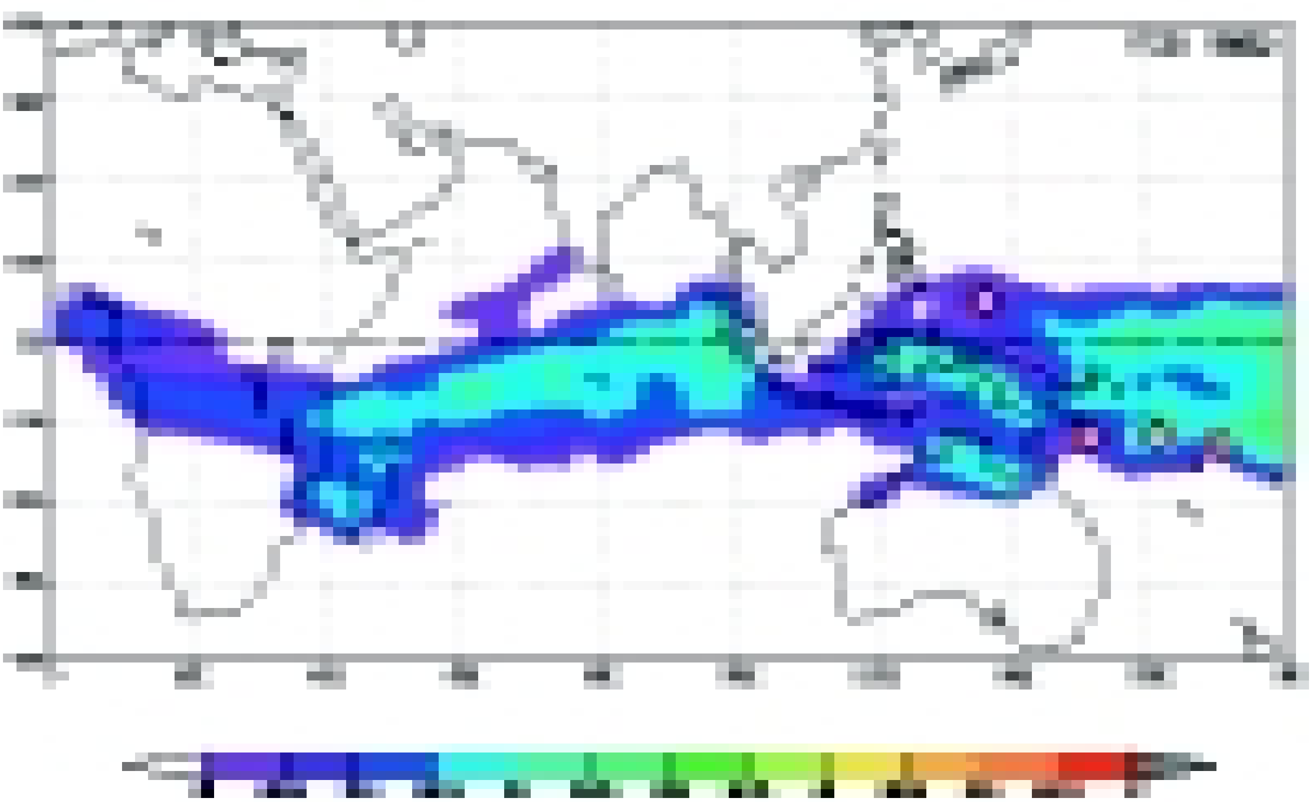


Figure 66
Tropical SST for February 1993. SST>28°C are shaded and the locations of all tropical cyclone genesis events for this month are indicated by bulls eyes.

Deep tropical convection rises buoyantly through the atmosphere and will be suppressed by subsidence. Hence, in regions of deep convection integrated vertical velocity (vertical motion, between 850-200mb, mass weighted and summed) is expected to indicate deep ascent. The integrated vertical velocity for February 1993 is plotted in Figure 67 and only regions diagnosed as undergoing large-scale ascent are shaded (once again, all tropical cyclogenesis locations are indicated). All tropical cyclogenesis events are in regions of deep ascent as expected. Comparison of Figures 66 and 67 demonstrates that in regions of integrated vertical ascent, SST > 28˚C. (The narrow region not shaded in the central Indian Ocean essentially integrates to zero). This coincidence between deep vertical ascent and SST > 28˚C is due to the incidence of deep tropical convection over water of these temperatures in the present climate. Intercomparison of these diagnostics for a five-year time period indicates that the integrated vertical motion may be used as a proxy for regions with SST > 28˚C in the present climate.

Two remaining environmental factors have been shown to impact tropical cyclogenesis: high relative vorticity and weak vertical wind shear. Each of the tropical cyclogenesis events were observed to form in regions in which high relative vorticity values were observed at least 12-24h prior to genesis (not shown).

The impact of tropical cyclones is not restricted to the tropical and subtropical regions, but extends deep into the mid latitudes in the form of intense rain and wind events.

Large values of vertical wind shear (difference between the horizontal wind vectors at 850mb and 200mb) at the time of genesis are expected to be detrimental to the development of the vertically stacked tropical cyclone. Vertical wind shear fields for February 1993 are plotted in Figure 68. Regions diagnosed with shear less than 15 ms^{-1}/(650mb) are shaded and all tropical cyclogenesis events are indicated. Almost all genesis events are in regions with shear less than 15 ms^{-1}/(650mb).

The overlap of shaded regions between Figures 66-68 coincides with the observed tropical cyclone genesis locations. Hence, the physical impacts of these environmental factors are observable even on time scales of a month. This is a favorable indicator that such diagnostics may be combined as a GCM "tropical cyclone frequency index."

Conclusions

In summary, we have explored the region of tropical cyclone impact, possible cross-dependencies between tropical cyclogenesis and SST, vertical wind shear and deep vertical ascent. Results highlighted here include:

1) demonstration that the impact of tropical cyclones is not restricted to the tropical and subtropical regions, but extends deep into the mid latitudes in the form of intense rain and wind events. The example of return period for extreme (≥ 200% of normal) rainfall events over the northeast U. S. (Figure 64) was used to illustrate this;
2) GCM sensitivity studies suggest that the threshold of SST > 27˚C presently regarded as the minimum SST for which tropical cyclogenesis can occur is likely to vary with different mean climate state (Figure 65);
3) Regions of integrated vertical ascent in the tropics are collocated with tropical SST > 28˚C, although there is not widespread ascent over the warmest equatorial waters. Since subsidence in tropical cyclones is predominantly restricted to the eye region (sub-grid scale in these analyses) large-scale integrated vertical ascent seems a good proxy for "suffi-

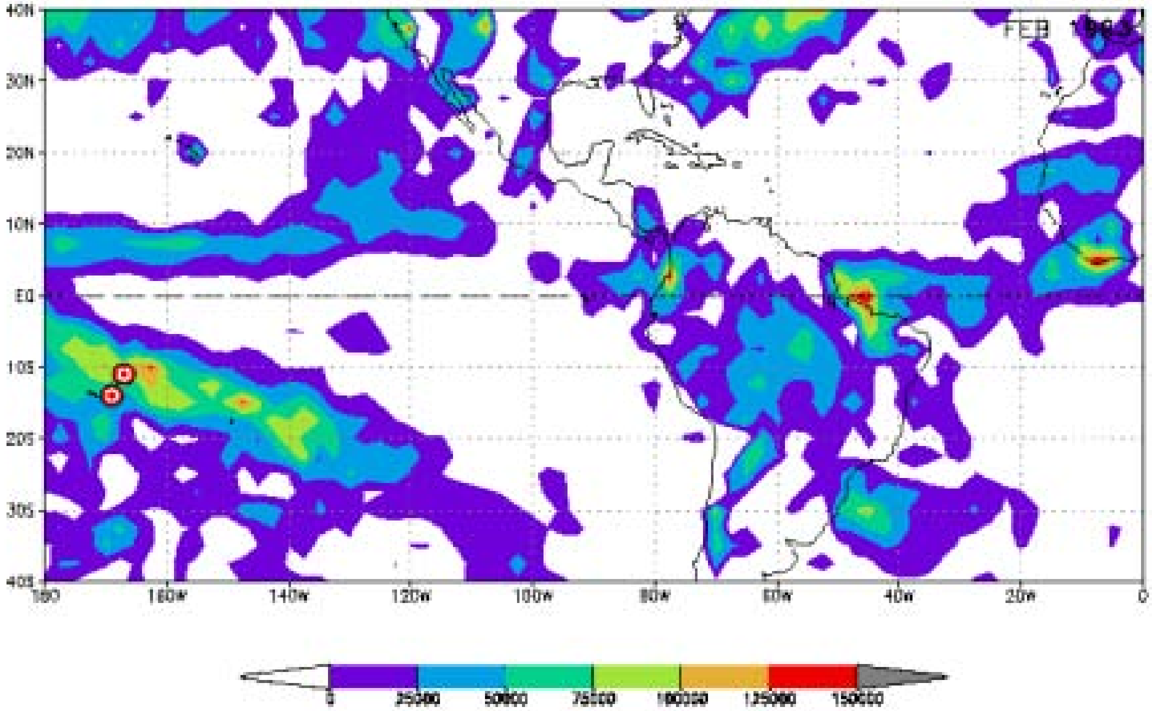


Figure 67
Integrated vertical velocity (vertical motion, between 850-200mb, mass weighted and summed) for February 1993. Only regions diagnosed as undergoing large-scale ascent are shaded and all tropical cyclogenesis locations are indicated.

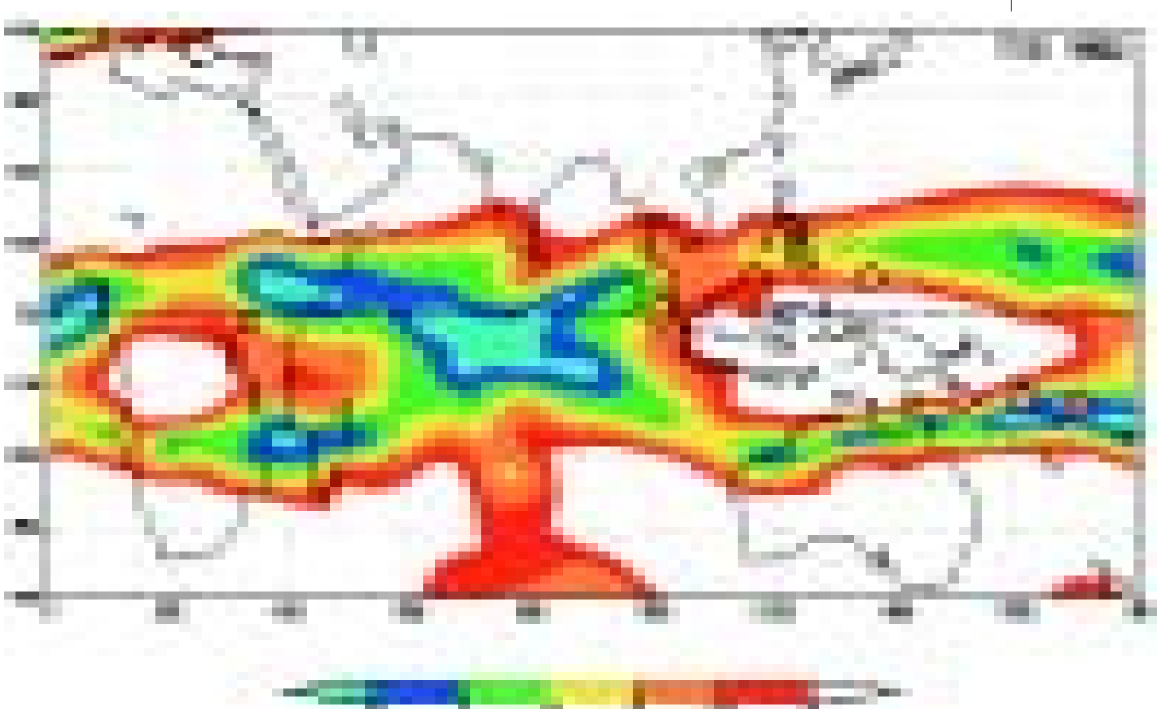


Figure 68
Vertical wind shear (difference between the horizontal wind vectors at 850mb and 200mb) for February 1993. Regions diagnosed with shear less than 15 ms^{-1}/(650mb) are shaded and all tropical cyclogenesis events are indicated.

ciently warm" SST and has the advantage of having a climate-independent threshold of zero (separating ascent and descent);

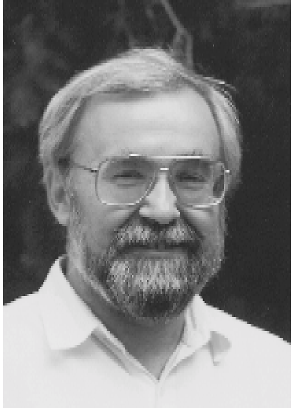
4) Deep vertical ascent and weak [$<15 ms^{-1}/(650hPa)$] vertical wind shear constraints go far in restricting the region of the tropics in which tropical cyclogenesis is viable. The overlap between these regions and those with cyclonic relative vorticity captures most of the variability of tropical cyclogenesis regions.
5) Combination of these three components — (1) deep vertical ascent; (2) weak vertical wind shear; and (3) cyclonic relative vorticity — into a "tropical cyclone frequency index" shows promise as a large-scale diagnostic for GCM simulations. Some further refinement is needed however, to ensure that the regions so defined do not include non-genesis regions and that the intraseasonal and interannual characteristics of tropical cyclogenesis variability are captured by these diagnostics.

Combination of deep vertical ascent, weak vertical wind shear and cyclonic relative vorticity into a "tropical cyclone frequency index" shows promise as a large-scale diagnostic for GCM simulations.

SESSION 2

Jenni Evans makes a point during group discussion while Tom Knutson looks on.

Heavy Precipitation in a Changing Climate



Pavel Ya. Groisman
Thomas R. Karl, David R. Easterling, Richard W. Knight, Paul F. Jamason, Kevin J. Hennessy, Ramasamy Suppiah, Cher M. Page, Joanna Wibig, Krzysztof Fortuniak, Vyacheslav N. Razuvaev, Arthur Douglas, Eirik Førland, and Pan-Mao Zhai
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A simple statistical model of daily precipitation applied to the data of eight countries shows that the shape parameter of the precipitation distribution remains regionally and temporally stable, the number of days with precipitation remains more or less stable, while the scale parameter is highly variable in time and space. This implies a likelihood that changes in mean monthly precipitation in these countries will be associated with disproportionately large changes in the extremes. When mean summer precipitation increases by 5%, similar to what has occurred in several regions during the past century, with no change in the number of precipitation days and no change in the shape parameter of the precipitation distribution, there is a 20% increase in the probability of summer daily precipitation over a 25.4 mm threshold in northern countries (Russia, Canada, Norway, and Poland) or a 50.8 mm threshold in mid-latitudes, tropics, and subtropics (the United States, Mexico, China, and Australia). That is, the increase in the probability of "heavy" precipitation is four times the increase in mean precipitation. Our results indicate that in a warmer and wetter world, as projected by climate models driven by increasing greenhouse gases, increases in heavy precipitation are likely to be disproportionately large compared to any change in the total precipitation. This is likely to have important socio-economic and ecological impacts. This feature of summer precipitation may already be manifested in recent increases in precipitation extremes over some regions, *e. g.*, the United States and Australia (Karl *et al.* 1995; Karl and Knight 1998; Suppiah and Hennessy 1996, 1998; Table 13).

The increase in the probability of "heavy" precipitation is four times the increase in mean precipitation.

Analyses of trends in mean precipitation during the past century reveal compelling evidence of the presence of trends over many regions of the world (IPCC 1996). Of particular interest, from both practical and theoretical considerations, are the analyses of precipitation change that reveal increases in extreme and very heavy precipitation from North America, Australia, Japan, and Europe. Generally, climate model simulations also consistently project increases in global precipitation due to global warming stemming from increases in greenhouse gases and an increase in heavy precipitation. We focus on heavy precipitation during the three warmest (and often wettest) summer months, which coincide with the period of the primary growing season, and assess heavy precipitation changes in eight countries: Canada, the U. S., Mexico, the former Soviet Union, China, Australia, Poland, and Norway (Figure 69). These constitute more than 40% of the global land mass, and more than 80% of the extratropical land area.

A simplest and widely recognized model was used to describe the distribution of daily precipitation totals. Under this model, it is assumed that the occurrence of daily precipitation

events has a binary distribution with the probability of a single event P_{pr} and the distribution function of precipitation totals F(x) is expressed as:

$$F(x) = P(X \leq x) = (1-P_{pr}) + P_{pr} \int_{o}^{x} p(\eta, \lambda, \tau)\, dt \qquad (1)$$

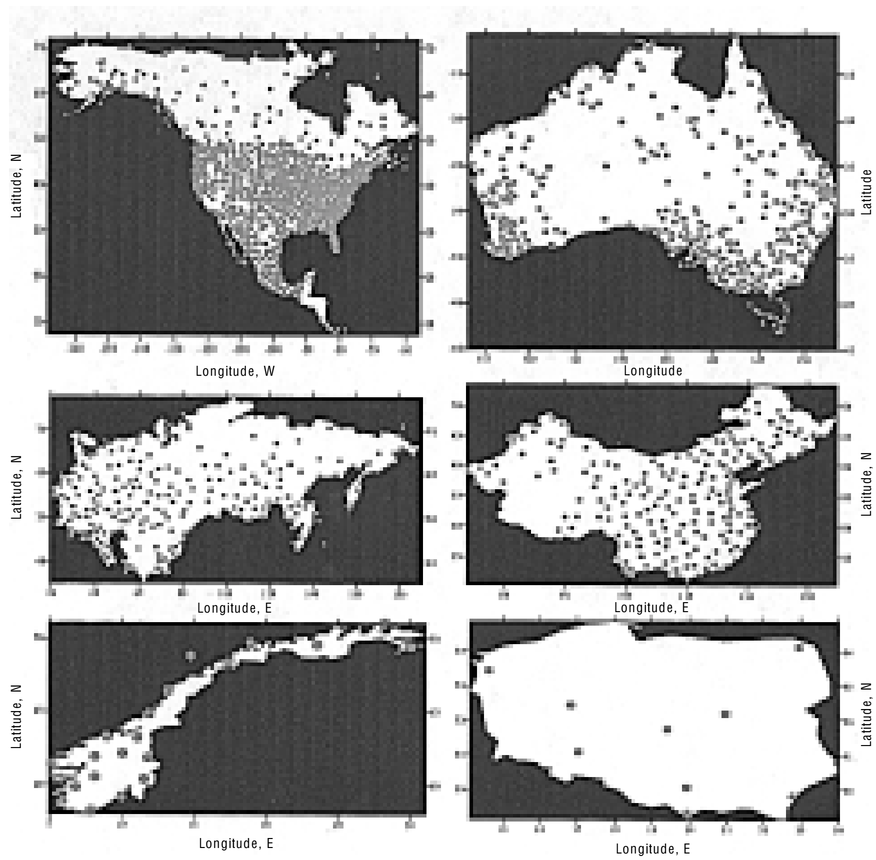

Figure 69
Maps of the stations with daily precipitation time series used in this study for North America (Canada, the U. S. and Mexico), Australia, the former Soviet Union, Peoples Republic of China (PRC), Norway, and Poland. Only the continental part of all these countries is shown. Several stations from adjacent islands were also used in the analyses. Note the different spatial scales in each map. The data span 45 (PRC) to 100 (the U. S., Norway, Australia) years. The daily precipitation time series were quality controlled and homogenized (where necessary) before their use.

In a warmer and wetter world, increases in heavy precipitation are likely to be disproportionately large compared to any change in the total precipitation. This is likely to have important socio-economic and ecological impacts.

The precipitation amount during this event is considered to have a two-parameter gamma-distribution, $p(\eta, \lambda, \tau)$. For this model, we have three parameters: P_{pr}, η and λ. The η-parameter defines the shape of the distribution, while the λ-parameter characterizes the scale/intensity of precipitation during the days with precipitation. We applied this model to daily precipitation totals over Eurasia, Australia, and North America but beforehand, we tested the fit of model (1) for estimates of the probability of heavy rains in the regions with a dense network of long-term homogeneous precipitation observations with a sufficient amount of precipitation events (Eastern U. S., Eastern Australia, European Russia, Southern Norway).

We calculated empirical estimates of the probability of "heavy" precipitation (*i. e.*, above a given threshold), compared them with calculations based on model (1), and found that for the thresholds under consideration, model (1) reproduces the pattern and absolute values of probability reasonably well. Analysis of spatial and temporal variability of the parameters of model (1) shows that the η-parameter is less variable in space and time. It varies but little in the march of seasons, between wet and dry summers at the same locations, and spatially over the continents. This suggests that in moderate climatic change this parameter will probably stay intact and not contribute significantly to the changes in mean precipitation over the regions with mean daily precipitation above 1 mm per day. Over the U. S., Norway, and Australia, we found an increase in summer precipitation frequency (*i. e.*, P_{pr}) over the past century. But when the same analyses are repeated only for the post-World War II period, they do not show statistically significant trends in P_{pr} over all eight countries.

The mean, μ, variance, σ^2, and the coefficient of variation C_v of this distribution are defined by P_{pr}, η, and λ parameters. For example, the mean precipitation in model (1) is a product:

$$\mu = P_{pr}\eta/\lambda \qquad (2)$$

and its change can be a result of the contribution of all three parameters. We are interested in the changes in the probability of heavy rains that can accompany changes in mean precipitation. Therefore, we tested the sensitivity of this probability to changes in μ that are introduced by the variation of each of these three parameters. In the regions with mean daily summer precipitation above 1 mm per day for typical combinations of η, λ, and P_{pr}, the change in the probability of exceeding heavy precipitation thresholds with a change in μ was analyzed. The strongest changes in heavy precipitation probability occur when the changes in μ are associated with variation of scale parameter, λ, and the smallest changes occur when the changes in μ are associated with variations of P_{pr}. For example, the probability of exceeding a 50.8 mm day^{-1} threshold over the eastern two-thirds of the contiguous U. S. with a 10% increase in μ changes by approximately 40%, 20%, and 10%, if this increase in μ is produced in Eq. 2 by an appropriate change in λ, η, or P_{pr} respectively. Obviously, an increase/decrease in P_{pr} produces a linear 1:1 increase/decrease in probability to exceed any given threshold. Changes in the two other parameters produce disproportionately high changes in the probability of extreme precipitation compared to the corresponding changes in mean precipitation (Figure 70).

Over the U. S., Norway, and Australia, we found an increase in summer precipitation frequency.

We presume that for daily precipitation described by (1), the changes in λ, η, or P_{pr} which have occurred interannually and in the seasonal cycle during the past century as well as their spatial variability contain information about the stability of these parameters in moderate climate and weather variations. Then, using this information, we can apply a plausible scenario of the mean precipitation change and derive valuable information about the most probable change in precipitation extremes. We consider scenarios of the small/moderate increase of mean precipitation that match the precipitation changes during the past 100 years over the countries under consideration. We estimate parameters of model (1) for the period of the mass data availability and then use them to test the present and future tendencies in heavy precipitation (Figure 71, Table 14). For example, in Figure 71 we define

"heavy" precipitation, P_{heavy}, as a daily precipitation exceeding the 25.4 mm threshold in northern countries (Russia, Canada, Norway, and Poland) and exceeding the 50.8 mm threshold in mid-latitudes (the U. S., Mexico, China, and Australia) and estimate the disproportionate increase in precipitation for heavy precipitation rates, compared to a 5% increase in mean precipitation, if the shape of the precipitation distribution and the probability of a precipitation event do not change. Table 14 presents a scenario of the most-probable changes in the probability of summer heavy rainfall, P_{heavy}, above 25.4 mm over Norway derived from the recent variations in m, and P_{pr}.

Which of these three parameters will be responsible for the change in the mean precipitation will substantially affect the behavior of precipitation extremes and, in turn, will have important socio-economic and ecological consequences.

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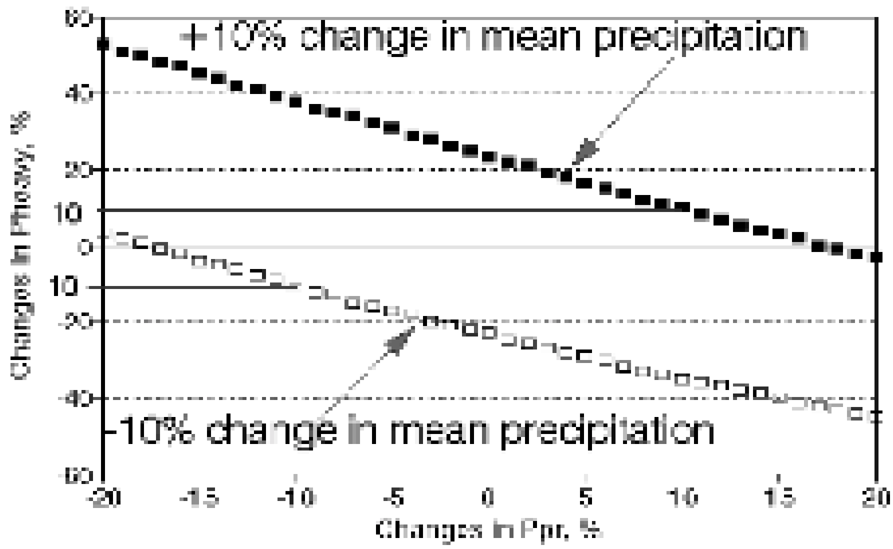

Figure 70

Changes in the probability of heavy rains, P_{heavy}, (above 50.8 mm) in Guangzhou, PRC (P_{pr} = 0.6; η = 0.56; λ = 0.04 mm^{-1}; μ = 8 mm day^{-1}) with a 10% increase/decrease in mean summer precipitation, μ, assuming that η does not change and the changes in μ are due to changes in P_{pr} and λ. Because $\mu = P_{pr}\eta/\lambda$, the changes in λ in these scenarios are a function of $\Delta\mu$ (= ± 10%) and ΔP_{pr} and are not shown. This figure shows that depending upon the ratio of changes in these two parameters to the change in μ, P_{heavy}, can change

- with a higher than linear rate, when changes in P_{pr} are less than the changes in μ by absolute value;
- linearly, when changes in μ are solely due to changes in P_{pr} (fixed λ);
- with a lower than linear rate or inversely (in this example, when absolute values of ΔP_{pr} are above 17%), when changes in P_{pr} are higher than the changes in μ by absolute value.

Therefore, in constructing scenarios of a future climate change, we have to judge which of these three parameters will be responsible for the change in the mean precipitation. This will substantially affect the behavior of precipitation extremes in these scenarios and, in turn, will have important socio-economic and ecological consequences. Although this figure shows a variety of P_{heavy} changes depending upon changes of the ratio of P_{pr} and λ, in our analyses, only *one* combination/realization has been observed in each region where we have sufficient homogeneous precipitation data on a century time-scale (the eastern two-thirds of the U. S., coastal regions of southeast Australia, European part of the former USSR, and southern Norway): the changes in P_{pr} are of the same sign and less than the changes in μ by absolute value. This implies (according to our model) that the changes in P_{heavy} will be in the same direction as changes of μ with a higher than linear rate. This is exactly what we have observed in our empirical estimates of P_{heavy}.

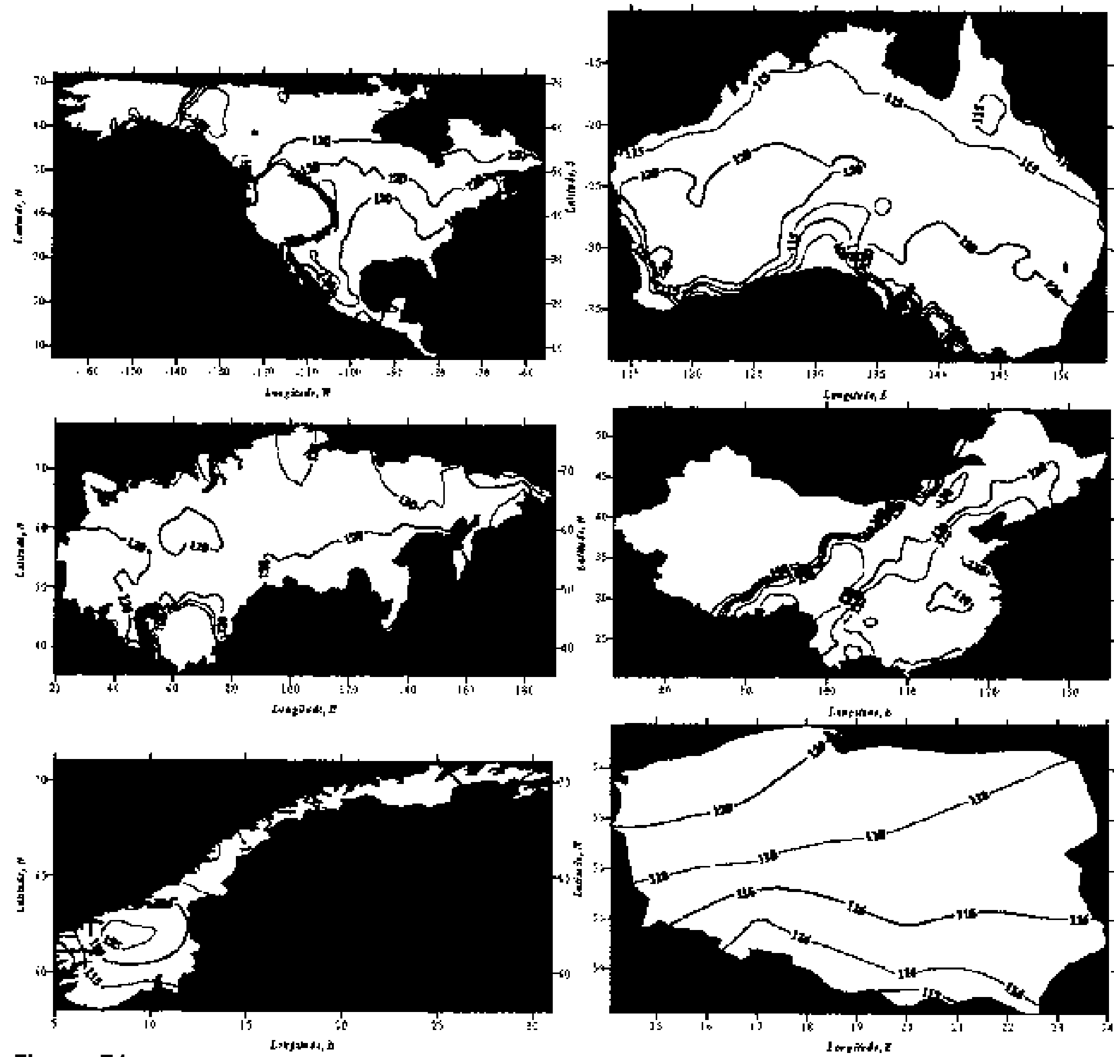

Figure 71

Percentage change of the probability of summer daily precipitation exceeding the heavy rainfall thresholds, P_{heavy}, (defined in text) when the mean daily precipitation increases by 5% assuming that P_{pr} and h do not change. The change is expressed as a ratio P_{heavy} (scenario)/P_{heavy} (climate). In all eight countries considered (except China) at least a 5% increase in mean summer precipitation has been documented during the past 100 years (IPCC, 1996, 1998). In three countries (U. S., Australia, and Norway) we found a century-long increase in heavy precipitation frequency and in P_{pr}. In other countries, where we have shorter and/or insufficient data, the direct detection of systematic changes in heavy precipitation using observational data is more difficult. Therefore, we exploit our findings about the stability of η and P_{pr} (the temporal stability of P_{pr} is, however, dependent on the period of interest) and use various assumptions about how the mean precipitation may (or did) change to analyze the effect of these changes on extreme precipitation. As an example of this type of analysis, in this figure we present the effect of a 5% increase in mean precipitation on the precipitation above selected thresholds assuming a scenario of no changes in η and P_{pr}. We apply this scenario to all eight countries although summer precipitation in some of them (Russia, Canada, Australia, Norway, Mexico) has increased at a higher rate during the past century, while over eastern China it decreased. Particularly, in the eastern U. S., in regions with mean summer precipitation above 2 mm per day, an increase in mean daily precipitation by 5% yields an increase in the probability of daily precipitation above 50.8 mm (2 inches) by approximately 20%. In the Mississippi River Basin, up to half of the increase in mean summer precipitation is contributed by heavy rains. This helps explain why recent studies by Karl *et al.* (1995) and Karl and Knight (1998) were able to detect significant increases in extreme precipitation over the contiguous U. S., while the century-long increases in summer precipitation totals over the same region were non-significant.

In all eight countries considered (except China) at least a 5% increase in mean summer precipitation has been documented during the past 100 years.

In the Mississippi River Basin, up to half of the increase in mean summer precipitation is contributed by heavy rains.

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Table 13

Country-wide linear trends of the number of summer days with heavy precipitation over the contiguous U. S., Australia, European part of the former Soviet Union, and Norway. Asterisk indicates a statistically significant difference from zero at the 0.05 significance level.

Country	Period	Threshold used to define "heavy" rain	Average number of days with heavy rain	Linear trend day/10years	Linear trend %/10years
Contiguous U. S.	1910-1996	50.8 mm	0.4	0.007*	1.7*
Eastern two-thirds of the contiguous U. S.	1910-1996	50.8 mm	0.6	0.010*	1.7*
European part of the former USSR	1936-1994	20 mm	1.8	0.069*	3.9*
Australia	1910-1996	50.8 mm	0.7	0.018	1.1
Coastal regions of New S. Wales and Victoria	1900-1996	50.8 mm	0.4	0.019*	4.6*
Norway	1901-1996	25.4 mm	2.0	0.04	1.9

Table 14

Scenario of the most-probable changes in the probability of summer heavy rainfall, P_{heavy} above 25.4 mm over Norway derived from the recent (past 60 years) variations in mean precipitation, μ, and frequency, P_{pr}. In these scenarios we continue to fix η. Average numbers of days with heavy rainfall and their linear trends estimated from the century-long homogeneous time series for period 1901-1996 are also shown. In order to better match the observed precipitation changes for this country we should split the observed increase in mean precipitation between increases in intensity and frequency. In this Table we present our best guess scenarios for extreme precipitation changes in Norway. A scenario below is based on the analysis of the summer mean precipitation and frequency changes over the past century: a 7% increase in mean summer precipitation in the "windward" part of the country (all northern Norway and coastal ocean-front part of southern Norway) and a 5% increase in the number of rainy days; a 7% decrease in mean summer precipitation in a "leeward" part of the country (interior and southeastern part of southern Norway, south of 62.5°N and east of 6°E) without any changes in precipitation frequency. Under this scenario changes in P_{heavy} are less prominent but, nevertheless, still higher than the changes in mean precipitation. Empirical estimates of century-long trends in the number of days with heavy rainfall support this analysis and the order of magnitude of these trends is consistent with theoretical estimates of changes in P_{heavy}.

Region	$\Delta\mu\Delta$ (%)	P_p (%)	ΔP_{heavy} (%)	Average number of days with heavy rains	and their linear trend %/100 years
Windward part of the country	+7	+5	12	2.9	14
Leeward part of the country	-7	0	-26	1.3	-20

The scenario results have been favorably compared with direct estimates of trends in heavy precipitation during the past 100 years over the U. S., Australia and Norway. For these countries, we possess sufficient century-long homogeneous time series of daily precipitation to evaluate the trends in heavy precipitation directly, *i. e.*, without the help of model (1). These data support our conclusions about the century-long disproportionate increases in heavy precipitation. To be conclusive, analyses of country-wide trends in heavy precipitation have to be based on a more dense network than similar analyses for mean precipitation, because of the low ratio of signal to noise in the data. However, the approach used in scenarios shown in Figure 71 can handle the data paucity problem.

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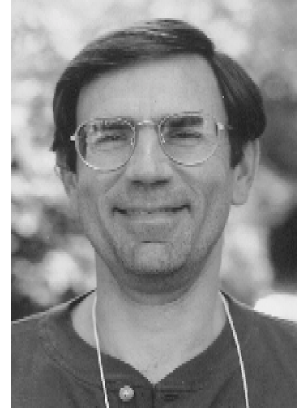
Climate Extremes: Selected Review and Future Research Directions



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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:

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.

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, which 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 of 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.

The Context

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 1980s 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 extreme 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.

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 human-built 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.

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.

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:

- 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?

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 discernable 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.

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).

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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 of sectors such as agriculture (growing season length and pest control) and power generation and consumption. For example, Cooter and LeDuc (1995) report that in the northeastern U. S. over the 1950-1994 period the frost-free period begins about 11 days earlier in the 1990s compared to the 1950s, and Easterling (1998) has shown that for the 1948-1995 period, the northern Great Plains and Great Lakes regions have experienced a decline of nearly 3 days per decade in the number of days where the minimum temperature is below freezing. 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 U. S. 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 U. S., 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 and increase of mean temperatures in the U. S. 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.

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 1974-1993 and 1954-1973 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 (U. S., 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.

Precipitation

Intense Precipitation

There has been a very significant increase in extreme precipitation events during the Twentieth Century in the U. S. due to both an increase in the frequency of very heavy and extreme precipitation events as well as an increase in their intensity.

There have been a number of large flooding events in the 1990s in Europe, Asia, and the U. S. 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 Australia 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 rain days 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 U. S. 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 have now been run for Canada (since 1941), the former Soviet Union (since 1967), and Australia (since 1910) with less striking changes than those seen in the U. S., 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 have 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 totals 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).

Droughts and Floods

IPCC 1990 concluded that analyses at that time showed little suggestion of an increase in the area of the globe affected by droughts and floods. More recent work however (e. g., Karl et al., 1995) indicates that in the U. S. 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 U. S., 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 1970s shift to more frequent and intense ENSOs may be a manifestation of the PDO (Mantua, et al. 1998).

In the U. S. 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.

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.

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 U. S., 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.

Tropical cyclones are the costliest natural disasters around the world.

Extratropical cyclones

Once again there is a dearth of analyses on the trends of intense extratropical cyclones, and some analyses have shown conflicting results. 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 North 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.

Loss Reduction Prospects

Reducing the human suffering and economic losses that result from extreme weather and climate 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 of 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.

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 temperature 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 relationship of the anthropogenic greenhouse effect to changes in temperature variability is 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 (see Figure 72). 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)
- An increase in extratropical storm severity (Lambert, 1996)

Many of these changes are consistent with the conceptual model (Figure 72) 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

Our observing systems and data sets often have large systematic biases of uncertain magnitude casting doubt on our ability to detect multi-decadal changes.

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.

There are some indications, although by no means is the argument unequivocal, that the hydrologic cycle is growing more intense.

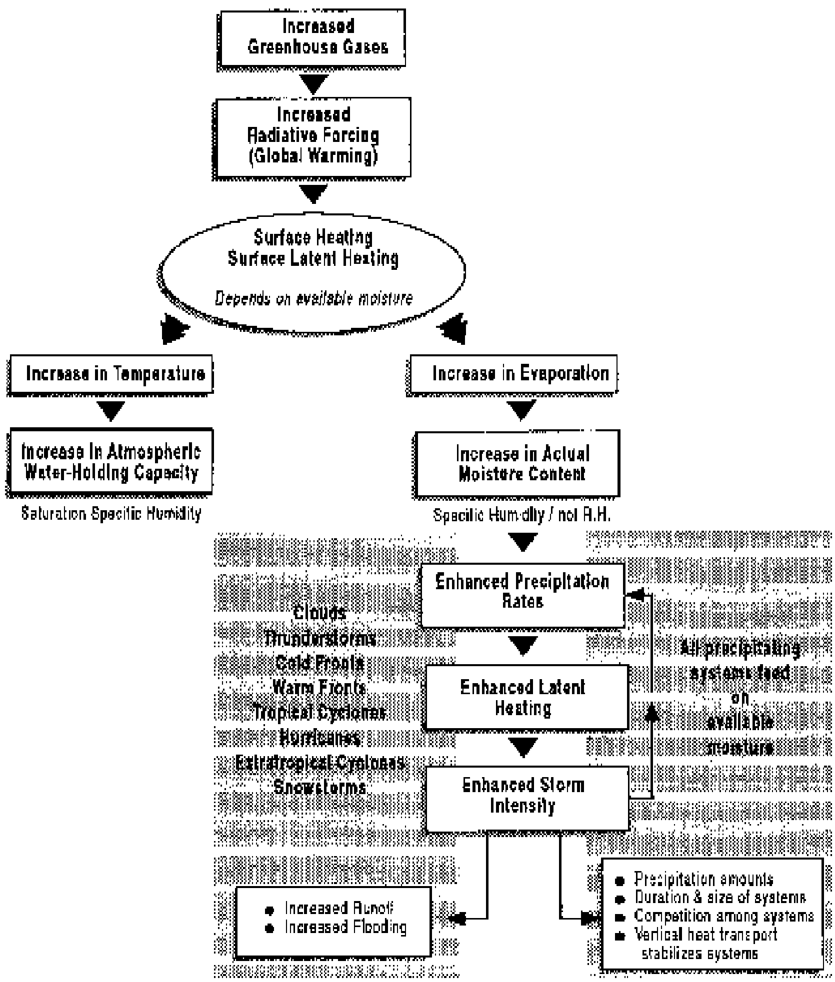

Figure 72
Conceptual model of the effect of greenhouse gases and global warming on the hydrologic cycle and phenomena associated with many climate extremes (from Trenberth and Shea, 1996).

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.

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.

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.

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 World Meteorological Organization's (WMO's) Data Rescue Project are called for to improve our information about changes in 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 be 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:

The highest priority in the design and implementation of new environmental observing systems should be given to data-poor regions.

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 extratro-

pical 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 tornados, 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.

There are few venues at present 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.

Climate monitoring can no longer be relegated to weather operations; the scientific basis, rationale, and oversight for long-term monitoring of climate and weather extremes must be given high priority.

Conclusions

Several important questions have been posed regarding climate extremes and natural hazards; we do not yet have satisfactory answers to some of these. Existing data indicate 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, some hints are emerging 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; the scientific basis, rationale, and oversight for long-term monitoring of climate and weather extremes must be given high priority.

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 Programs Climate and Global Change Program and by a U. S. Dept. of Energy Interagency Agreement.

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Inadequate data access and poor climate monitoring practices are two primary issues that must be improved.

Tom Karl looks over data with Rick Sylves.

Increased Hurricane Intensities with CO_2-Induced Warming
as Simulated Using the GFDL Hurricane Prediction System

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We examine primarily the question of possible CO_2-induced changes in the intensities of strong hurricanes.

SESSION 2

How would future hurricanes be affected by climate warming due to increased greenhouse gases? In this study, we examine primarily the question of possible CO_2-induced changes in the intensities of strong hurricanes. We do not address possible changes in storm frequencies or locations of occurrence. Observational studies of hurricane intensities versus sea surface temperature (SST) suggest an increase in the upper limit intensities of tropical cyclones with increasing SST. However, such an empirical SST/intensity relationship can not be reliably extrapolated to the question of hurricane intensity changes under CO_2-induced warming, since other environmental factors, such as the vertical structure of the atmospheric temperature changes, wind shear, and large-scale regions of ascent and descent, may also change in various ways regionally.

To address this problem quantitatively, we use the Geophysical Fluid Dynamics Laboratory (GFDL) regional high-resolution hurricane prediction system to simulate the behavior of samples of hurricanes under both present day and high CO_2 climate conditions. The hurricane model is the one presently used for operational hurricane prediction at the National Centers for Environmental Prediction (NCEP) and was developed at GFDL by Kurihara, Tuleya and Bender. The model focuses in on the near storm region using movable nested grids of increasing resolution. The inner-most grid has resolution of about 18 km, allowing the model to simulate more realistic hurricane structure and very strong intensities — features which cannot be simulated using the present generation of global climate models. The high resolution grids move with the storm during the experiments so that enhanced resolution can be maintained in the near-storm region without being required in the entire domain.

In our case study approach, 51 northwest Pacific storm cases under present-day climate conditions are simulated with the regional model, along with 51 storm cases for high CO_2 conditions. To run the regional model experiments requires a set of initial conditions and boundary conditions, such as SST. These are derived from control and transient CO_2 increase experiments with the GFDL R30-resolution global coupled climate model, which has much lower resolution than the regional hurricane prediction model. For each storm case, the regional model is integrated forward for five days without ocean coupling (*i. e.*, the storm is not allowed to influence the underlying SST). The northwest Pacific basin was chosen for emphasis in the study because the global climate model provides a more realistic

simulation of the occurrence of warm-core tropical-storm-like features in the northwest Pacific than in certain other tropical storm basins (particularly the northwest Atlantic).

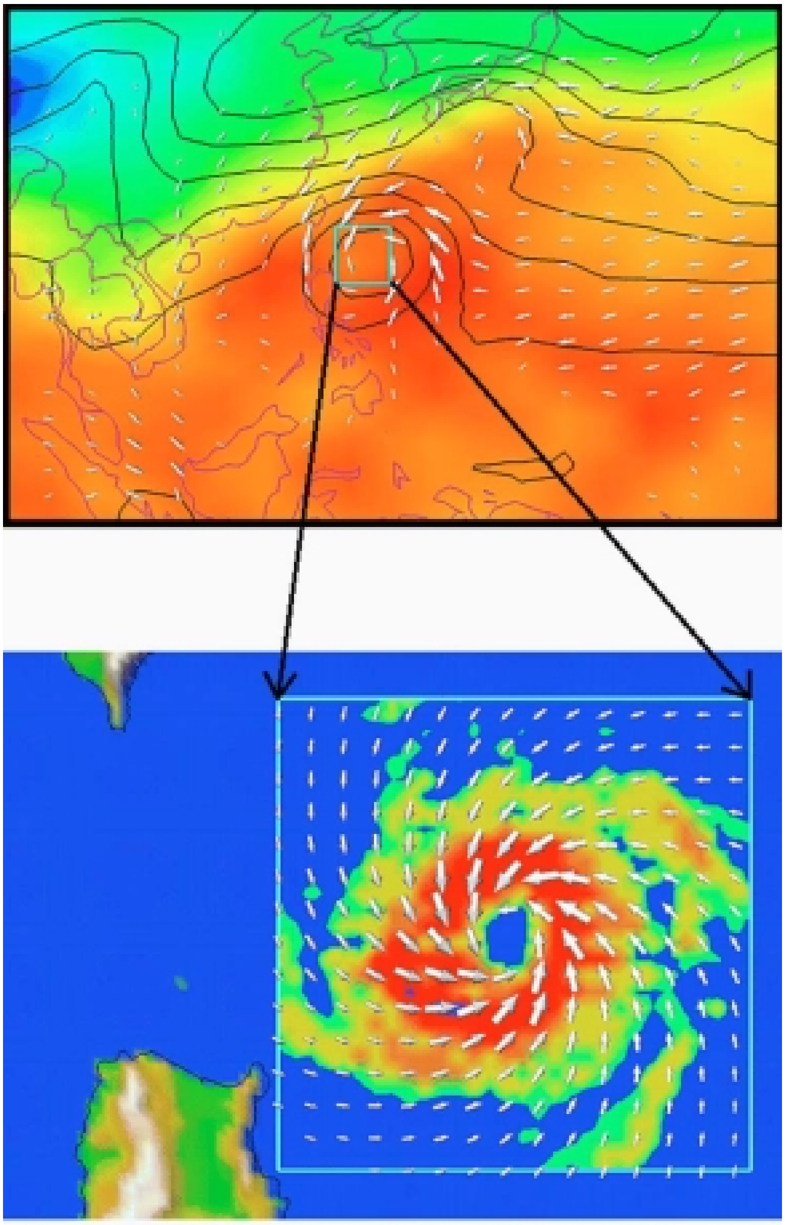

Figure 73
Top: a tropical storm as simulated in the global climate model. Shown are surface temperature (shading), pressure and winds. Bottom: the same storm case, but as simulated with the hurricane prediction model. Shown are surface winds and precipitation on the inner grid of the hurricane model. The vector spacing illustrates the resolution of the two models (~250 km for the global model versus ~18 km for the hurricane model.)

The high resolution grids move with the storm during the experiments so that enhanced resolution can be maintained in the near-storm region without being required in the entire domain.

The high CO_2 storms, with SSTs warmer by about 2.2°C on average, are more intense than the control storms by about 3 to 7 meters per second (5% to 12%) for surface wind speed and 7 to 23 millibars for central surface pressure. The simulated intensity increases are statistically significant according to most of the statistical tests conducted and are robust to changes in storm initialization methods. Near-storm precipitation is 28% greater in the high CO_2 sample. In terms of storm tracks, the high CO_2 sample is quite similar to the control, consistent with the rather similar large-scale mean atmospheric circulation in the control and high CO_2 climates of the global model. The storm tracks from the low-resolution global model have a more poleward trajectory than those of the high-resolution model, suggesting that in addition to storm structure and intensity, storm tracks may also be affected by the model resolution.

More idealized experiments were also performed in which an initial storm disturbance was embedded in highly simplified flow fields using time mean temperature and moisture conditions from the global climate model. These idealized experiments support the case study results and suggest that, in terms of thermodynamic influences, the results for the northwest Pacific basin are qualitatively applicable to other tropical storm basins.

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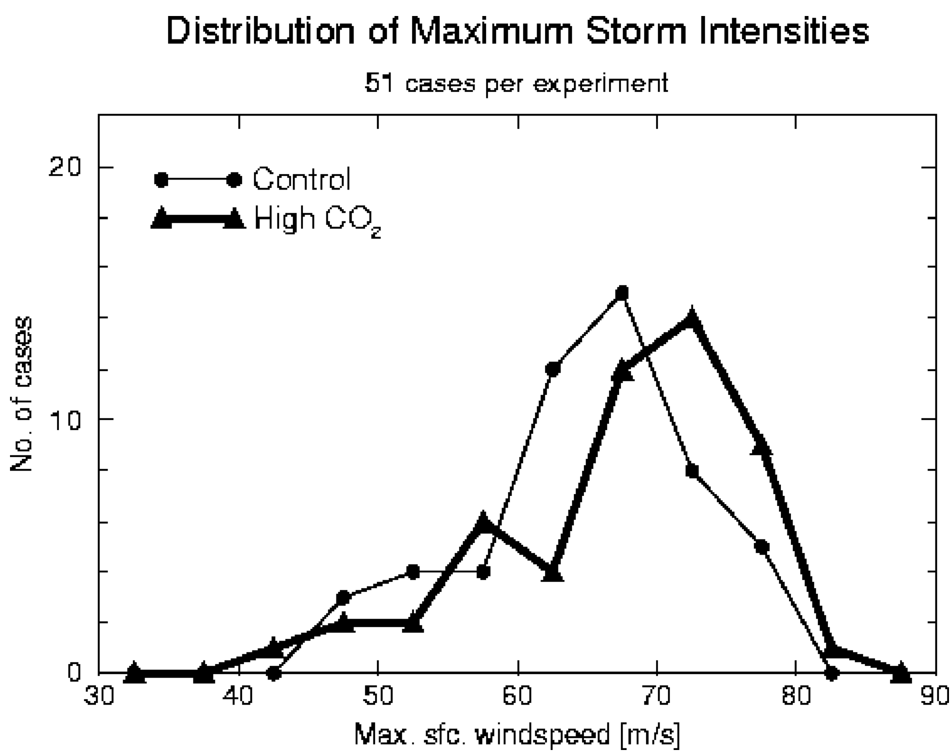

Figure 74
Maximum surface windspeeds for the hurricanes simulated for control (thin line) and high CO_2 (thick line) conditions. Unit: meters per second.

The results of the experiments can be compared with theories of maximum potential intensities (MPIs) of tropical cyclones. These MPI theories (developed by Dr. Kerry Emanuel of MIT and later by Dr. Greg Holland of CSIRO in Australia) both indicate an increase in the upper limit intensities of tropical cyclones in a high CO_2 climate, with the amount of predicted intensification being fairly similar to that simulated in our study. Both the MPI methods and our simulation approach (as applied to the northwest tropical Pacific), yield fairly realistic geographical distributions and magnitudes of the strongest hurricane intensities in the present climate. These results suggest that our methodology may provide a useful approximation to the actual sensitivity of strong hurricane intensities to a CO_2-induced global warming.

Near-storm precipitation is 28% greater in the high CO_2 sample.

Tom Knutson makes a point during group discussion while Mike Changery looks on.

Regional Variations in Extreme Temperature and Precipitation Trends in the U. S.

Kenneth E. Kunkel
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Champaign, Illinois

This talk presents recent results of an analysis of trends in heavy precipitation events that are related to flooding, and in extreme heat and cold episodes.

SESSION 2

In recent years, extreme climatic events have caused major impacts in the U. S. Perhaps one of the most devastating events was the 1993 flood in the upper Mississippi River basin that resulted in an estimated $18 billion in damages. Other very serious floods occurred in California and Nevada in January 1997, Quebec in July 1996, and the Red River Basin in April 1996. A severe heat wave in July 1995 killed more than 500 people, primarily in the Chicago area. These events illustrate that society remains vulnerable to climatic extremes. They also raises question about whether there are long-term trends in the frequency of these types of extreme events. This talk presents recent results of an analysis of trends in heavy precipitation events that are related to flooding, and in extreme heat and cold episodes.

Analysis was performed on data from stations with nearly complete (less than 5% missing) data for the period 1931-1996. Analysis was also performed for the period 1896-1997 on data from a set of 246 stations for 9 states in the midwestern U. S. This analysis provides insight into trends in the early part of the 20th century.

Heavy Precipitation Events

For heavy precipitation events analysis, I defined “extreme” events as 7-day periods with precipitation totals exceeding a threshold for a 1-year recurrence interval. This definition of heavy precipitation events was chosen because such events are highly correlated with hydrologic flooding in some regions of the U. S. I recognize that events defined in this way may not be as closely related to flooding in other regions. For simplicity, I have applied a common definition across the entire U. S. For each station, the annual number of events of 7-day duration exceeding the 1-year threshold was identified. To assess regional trends for the conterminous U. S., station values were arithmetically averaged for climate divisions. Climate division values were then averaged with area weighting to derive regional and national values. The Kendall tau statistic was used to test for trends. This nonparametric test is useful for analysis of extreme climatic events which are not necessarily normally distributed.

A composite time series of 7-day, 1 year events for the conterminous U. S. was assembled (see Figure 75). The time series is notable for large interannual and decadal-scale variability. Several climate events noted for severe drought or moisture surpluses are easily evident in this extreme event time series. For example, droughts in the 1930s, early 1950s, 1963, 1976, and 1988 were characterized by a low number of heavy precipitation events. In

several years in the 1990s, as well as 1941 and 1957, the U. S. experienced a high number of heavy precipitation events. Decadal-scale variability is substantial. Periods of below average frequency in the 1930s and 1950s were separated by a period in the 1940s of above average frequency. The 1960s and 1970s were characterized by generally low interannual variability and near to slightly above average frequency. Increased interannual variability is observed in the 1980s and 1990s with many years experiencing above average frequency. A linear trend analysis using the Kendall tau statistic indicates that the overall trend is upward at a rate of about 3% per decade (see straight line in Figure 75). This trend is highly statistically significant.

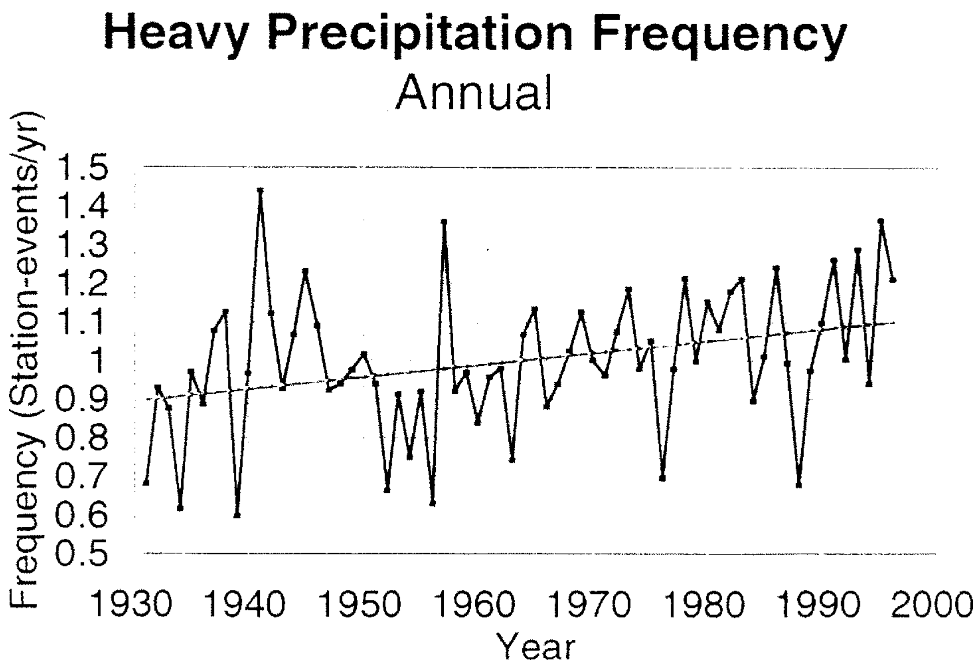


Figure 75
Composite index of the frequency of heavy precipitation events of 7-day duration exceeding a 1-year recurrence interval for 1931-1996. A linear fit to the data is shown by the straight line.

The overall trend in heavy precipitation frequency is upward at a rate of about 3% per decade.

The linear trend analysis was applied to the climate division time series. Significant upward trends (25% to more than 100%) have occurred over a broad region extending from the southwest U. S., across the central Great Plains and the middle Mississippi River basin and to southern Great Lakes basin.

The composite time series for each of nine climatic regions in the U. S., shown in Figure 76, generally show upward trends. Only the northwest and southeast U. S. have experienced overall downward trends.

The time series of total annual precipitation for the U. S., shown in Figure 77, shows an upward trend of about 1.3% per decade, which is statistically significant. The lower curve

shows the annual precipitation after removing the precipitation from the heavy precipitation events as defined here. These events account for about 15% of the total precipitation, but about 30% of the overall trend. That is, the upward trend in heavy precipitation events makes a disproportionate contribution to the overall trend in total precipitation.

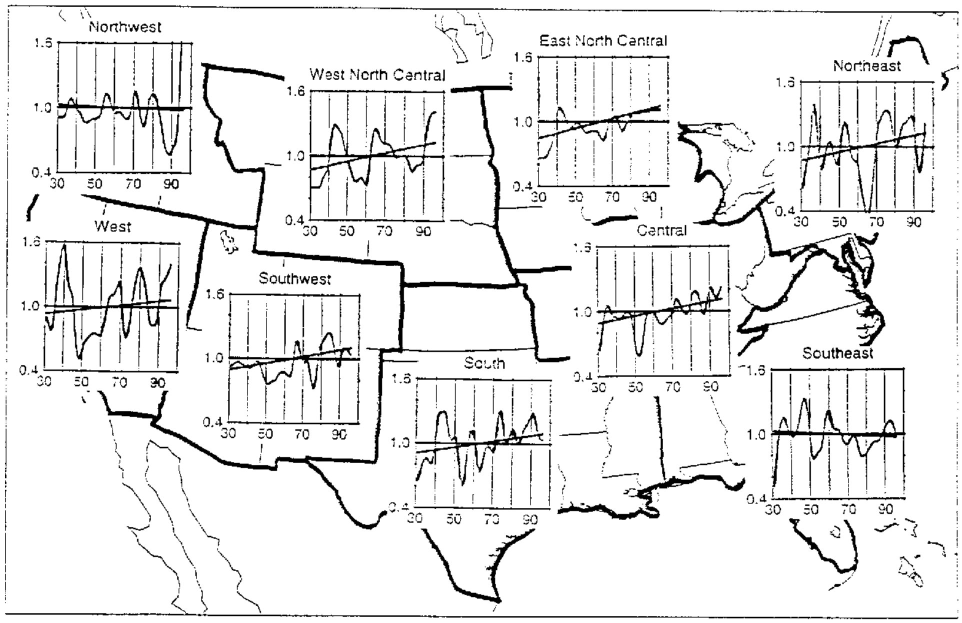


Figure 76
Frequency of 7-day 1-year heavy precipitation events for 1931-1997 for the 9 climate regions of the U. S. The straight line shows a linear fit to the data.

The upward trend in heavy precipitation events makes a disproportionate contribution to the overall trend in total precipitation.

A longer perspective on the changes on heavy precipitation events was provided by assembling a 101-year time series for the Midwest. This time series shows that the Midwest has experienced sizable multi-decadal variability in the frequency of heavy precipitation events. Around the turn of the century, the frequency was relatively high. The frequency decreased to a minimum in the 1930s and has generally increased since then. Thus, there is substantial century-scale variability in the frequency of heavy precipitation events.

Most of these heavy events tend to be clustered in time and space. Many stations experience a heavy precipitation simultaneously due to large scale systems. An analysis was performed by region on the top 20 periods with the most widespread episodes of extreme precipitation. Figure 78 shows the average 500 millibar (mb) height field, expressed as standardized departures, for the top 20 heavy precipitation events occurring in the Central Region. The flow pattern is highly meridional over the entire western hemisphere, reflecting extratropical wave activity. An examination of individual events indicates that these heavy precipitation episodes are caused by a slowly progressive long wave pattern with 2 to 3 short waves circulating around an upper level low, which brings several periods of moderate to heavy precipitation. This results in large precipitation accumulations over a 7-day period.

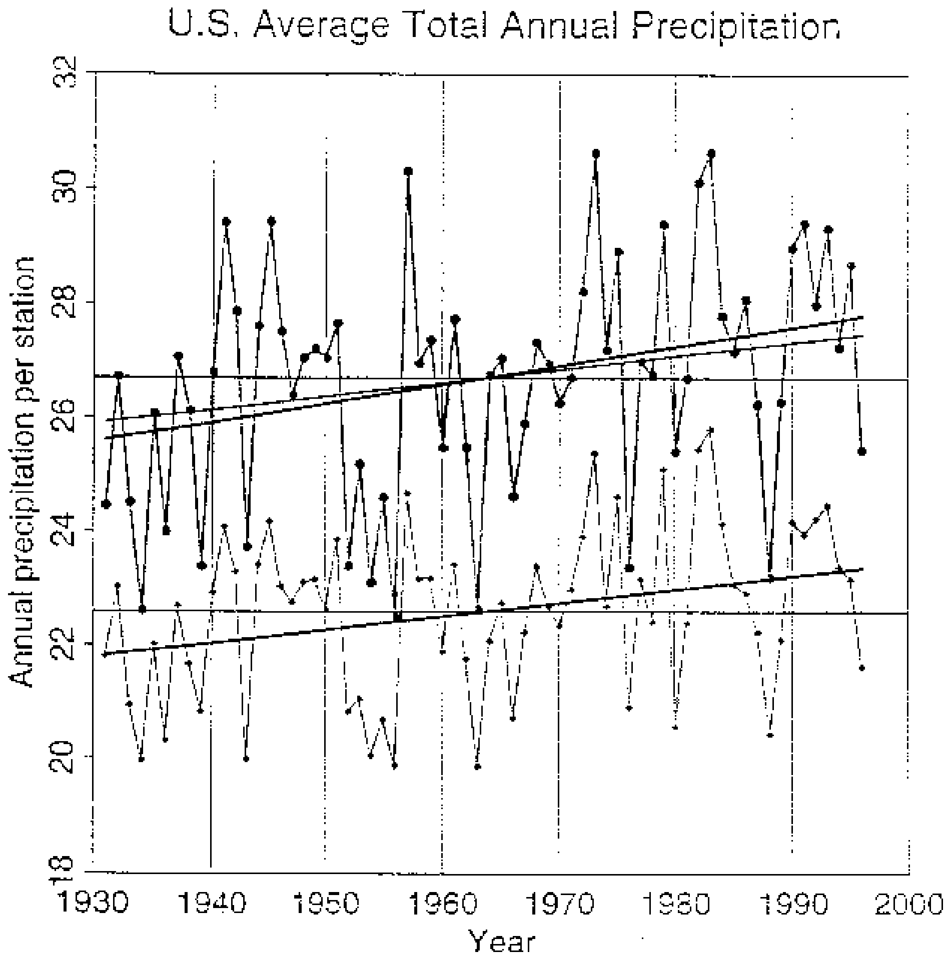


Figure 77
Average total annual precipitation for the U. S. for 1931-1997 (heavier line). The straight line shows a linear fit. The average annual precipitation minus that involved in 7-day l-year heavy precipitation events is shown in the lower curve.

The time series of total annual precipitation for the U. S., shown in Figure 77, shows an upward trend of about 1.3% per decade, which is statistically significant.

Heat and Cold Waves

The analysis of cold waves and heat waves used a similar approach regarding the definition of event, which was defined by a return period and a duration. A return period of 10 years was used to select only the most extreme temperature events. A four-day duration was used, which is sufficiently long to cause major health impacts, as illustrated by the 1995 heat wave. A national index of heat wave and cold wave occurrence for the period of 1931 to 1997 indicates that there was high frequency of cold wave events in 1963, 1983, and 1989. There is no obvious trend. With regard to heat waves, the highest frequency occurred in 1936 followed by 1934 and 1931. The extreme heat experienced during several years in the 1930s dominates the time series of heat wave. There is no obvious upward or downward trend since the 1930s.

These heavy precipitation episodes are caused by a slowly progressive long wave pattern with 2 to 3 short waves circulating around an upper level low, which brings several periods of moderate to heavy precipitation. This results in large precipitation accumulations over a 7-day period.

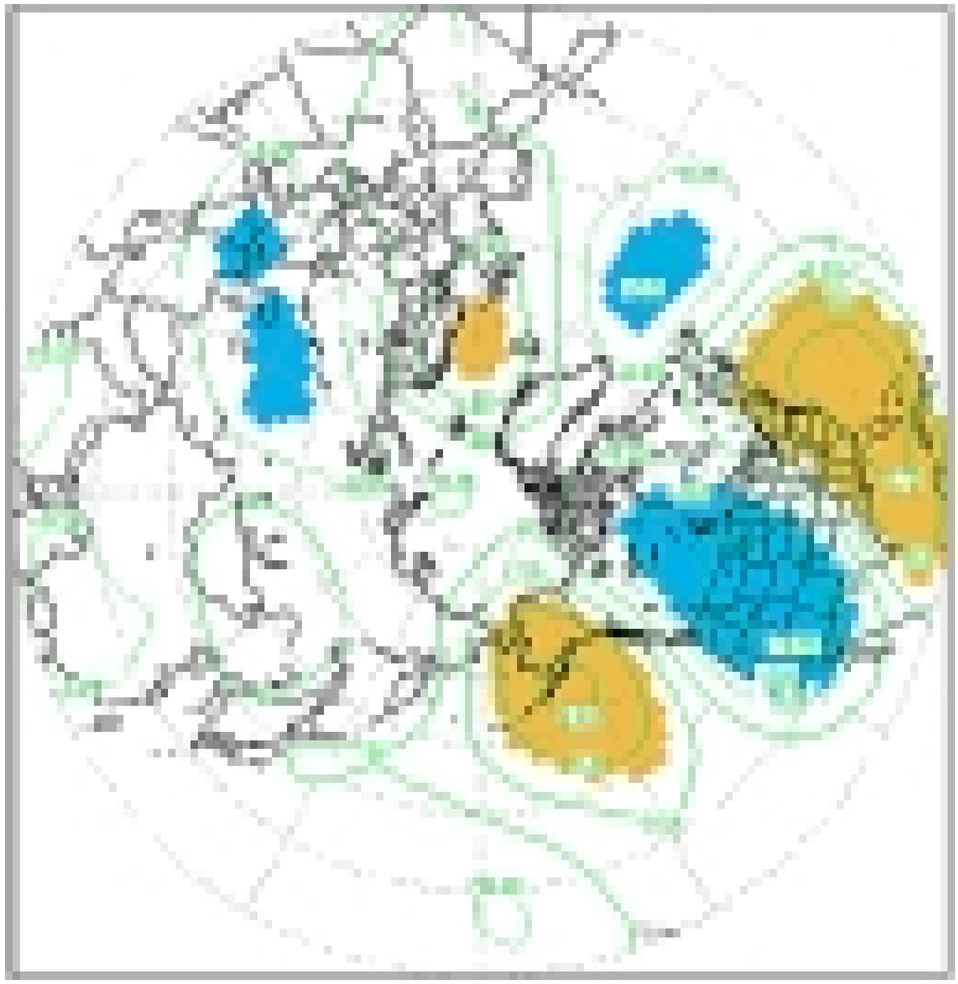


Figure 78
The averaged standardized departure in the 500 mb height field (m) for the 20 7-day periods in the central region of the U. S. with the most widespread occurrence of heavy precipitation events for the period 1947-1994.
The shaded regions are those with locally statistically significant departures from the normal, with dark gray indicating negative departures and light gray, positive.

A look at regional trends in cold wave frequency reveals substantial variability among the regions. Statistical tests indicate a significant increase in cold wave frequency in the East North-Central and Central Regions.

Looking at regional trends of heat wave frequency, in many regions, the 1930s stand out for the high frequency of extreme heat. There have been some recent episodes of extreme heat in the Southeast (1980s), Southwest (1990 and 1994), and the Northwest (1994).

Conclusions

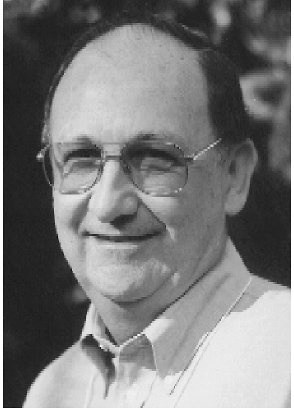
There is considerable regional variability in the trend of extreme climate events. Much of the U. S. has experienced an upward trend in the frequency of heavy precipitation events over the past 67 years. This trend is most notable in a belt extending from the southwest towards the central and northeast U. S. Most regions of the U. S. have not experienced an upward or downward trend in frequency of cold waves. With regard to heat waves, the 1930s stand out on a nationwide basis as a singular period of extremes.

These results raise some fundamental questions that deserve further research. These questions are as follows:

- What are the causal mechanisms for the observed decadal to century scale variability in a frequency of extreme precipitation events?
- What are the accuracies of GCM simulations of current climate with respect with the occurrences of the infrequent high amplitude wave activity responsible for some of the major extreme precipitation episodes?
- What are the causal mechanisms for the most disruptive extreme events of the century, the 1930s heat waves and droughts?

Much of the U. S. has experienced an upward trend in the frequency of heavy precipitation events over the past 67 years. This trend is most notable in a belt extending from the southwest towards the central and northeast U. S.

Peter Whetton and Jerry Meehl discuss trends in extreme events.



The Importance of Changes in Climate Extremes

for the National Assessment of the Potential Consequences of Climate Variability and Change for the United States

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As part of its responsibility of fulfilling the Global Change Research Act of 1990 that established the U. S. Global Change Research Program (USGCRP), a national assessment has been organized to evaluate and summarize the potential consequences of climate variability and change and capabilities for adapting and coping with such conditions. The assessment is being conducted under the leadership of the National Assessment Synthesis Team (NAST), which has been chartered as a federal advisory committee. Sponsorship and conduct of the assessment on behalf of the USGCRP are coordinated by the National Assessment Working Group (NAWG).

By looking at climate in the context of multiple stresses, the assessment is in some ways moving towards a focus on long-term sustainability.

SESSION 2

To provide insight into the rich regional and sectoral complexities of how variability and change can affect environmental and socio-economic aspects of the United States, twenty regional assessment teams and five sectoral assessment teams have been organized. The regional teams are using workshops and assessment activities to focus on consequences related to where one is located. They are accomplishing this by involving community and industrial stakeholders to help inquire, evaluate, and synthesize information on the local aspects of climate variability and change and its implications for regional activities and resources. Five sectoral teams, focusing on agriculture, forests, human health, water resources, and the coastal environment and marine resources, have been formed to consider the national scale aspects of these issues. All of these teams are led by scientists and all are working to closely involve stakeholders who are or in the future may be affected by global scale environmental variability and change.

The focus of the assessment is being driven by a number of interrelated themes.

- The first is that climate variability and change must be judged in the context of multiple stresses rather than as a separate issue, apart from how the world will be changing and how other stresses may be acting on the environment and society. By looking at climate in the context of multiple stresses, the assessment is in some ways moving towards a focus on long-term sustainability in future assessments.
- The second theme is time-scale. The assessment is striving to draw attention to timescales of 25 to 100 years, so working to focus attention on long-term issues that rarely receive sufficient attention in planning and regional development.
- The third theme is to focus attention on the potential for adapting and coping rather than on just the consequences and vulnerabilities in the absence of a response.

- The fourth key aspect is that the assessment is being designed to address problems and questions that are of particular interest to stakeholders — those who have a direct economic or other stake in what the outcome of the assessment will be.
- The fifth key aspect is to maintain scientific credibility, a requirement, that when combined with the previous ones, makes clear why the assessment must be a continuous and on-going effort that seeks to build a dialogue with stakeholders at the same time that there are enhanced and focused efforts to improve the state of scientific understanding.

The assessment effort is using a scenario-based approach to stimulate thinking and investigation of the potential importance of climate variations and change for the United States. In addition to posing a set of scenarios for socio-economic, technological, and demographic change and development that allows for a range of future conditions in the U. S., three approaches are being used as a means of considering the future climatic conditions that society may face.

- First, participants in the assessment are being asked to consider the potential consequences of a return of climatic fluctuations and variations that have occurred in the past (e. g., what would be the comparative effects today were the climatic conditions that led to the 1930s drought to return).
- Second, participants are being asked to consider the potential consequences for the U. S. of conditions that are projected to occur in a number of leading climate model simulations (e. g., what if the model-predicted warming and shifts in precipitation were to occur).
- Third, participants are being asked to identify the types of changes that, were they to occur, would put especially severe strains on the environment and on natural resource and/or societal system (e. g., while California may have designed its water system to withstand a 7-year drought, a 12-year drought may be the conditions that would have truly disastrous consequences for the stateís agricultural productivity). To provide estimates of the likelihood of such situations, participants are being asked to examine very long model simulations, the paleoclimatic record, and other indicators to attempt to estimate the potential for such extra-severe climatic conditions to occur. With this set of combined efforts, it is hoped that the vulnerability of the environment and of socio-economic activities can be identified, and perhaps coping actions can be identified that would help to enhance resilience to the variation or change.

Through this effort, it is hoped that the vulnerability of the environment and of socio-economic activities can be identified, and perhaps coping actions can be identified that would help to enhance resilience to the variation or change.

Although the effort is still in its formative stages, a number of interesting and useful insights are emerging, many of which make clear why it is so important to enhance our understanding of the range of variations of the climate that are possible due to natural factors and what changes in climatic variations, including in extremes, might be possible as a result of human-induced climate change. The insights are presently arising through stories from particular regions or sectors; it will be later in the process when general conclusions may be able to be drawn. For now, a few stories:

Industrial Vulnerability

Because reliability is so important to maintaining their customers and market share, many industries design their infrastructure and operations to be resilient to all but the most ex-

treme conditions — they find that it pays to protect against relatively low probability hazards because the loss of market share during down times can have long-term consequences on their economic health. Such industries want information on when climatic extremes may occur and how the range of climatic extremes may change over time so they can continue to make money in spite of the climatic fluctuations and changes that might occur.

Coastal Vulnerability

While one way of estimating the impacts of rising sea level is to consider the slow, long-term rise in sea level and its gradual impact on the coastline, it turns out that most of the erosional force of the rising ocean levels occurs during extreme conditions such as when tropical storms stir up ocean waves and create storm surges. The state of Louisiana is losing about 30 square miles of wetlands each year due to subsidence and sea level rise causing inundation; these coastal wetlands are the "shock absorber" that slows the windspeed and absorbs the onslaught of waves as hurricanes churn offshore and over the region. It is vital to understand how the frequency, intensity, direction, and duration of tropical storms may vary in order to understand the risk posed to coastal and near-coastal communities such as New Orleans.

Most of the erosional force of the rising ocean levels occurs during extreme conditions such as when tropical storms stir up ocean waves and create storm surges.

Flooding and Droughts — Southeast

Some regions of the U. S. turn out to depend on relatively periodic variations in wet and dry periods. For Florida, the variations caused by El Niños can lead to some regions first being inundated with rains that overwhelm the limited runoff and groundwater capacities of the region (causing floods) and then the regions can experience extended dry spells during which the limited groundwater capacity cannot supply the region's vegetation with sufficient moisture, exposing the region to increased potential for fires (as happened in Florida in 1998). Understanding better how such variations arise and whether they might intensify or subside would be particularly valuable for estimating the potential risk for various regions.

Flooding and Drought — Great Plains

In the northern Great Plains, as well as over mountain regions in the west, the build-up of snow in the winter and then its rapid melting in the spring can create flooding even in the absence of contemporaneous rainfall — and if rain accelerates the snowmelt, the situation is much worse. Whether rain or snow falls is thus very important, and this can depend on very subtle changes. That the annual cycle of precipitation may change, with temperatures being different as this happens, also raises the potential for quite significant changes in particular regions. If precipitation is snow and it suddenly melts, flooding can result; if precipitation comes as rain and runs off immediately, then the snowpack will not be there to provide summertime runoff and so drying may result. Gaining better insight into how these thresholds and non-linearities work is particularly important.

Hurricanes

The focus of recent studies about how climate change may affect hurricanes has been on potential changes in frequency and windspeed; these studies do not yet seem to be in agreement, with differing studies giving differing results for changes in these variables. However, the major cause of environmentally induced death in Latin America, for example, is actually the flooding rains that can result from tropical storms and hurricanes, and the rainfall amount

(which can exceed 20 inches in 24 hours) is not particularly dependent on the peak windspeed that determines the destructive category of the hurricane. An initial study by GFDL scientists Thomas Knutson and Robert Tuleya suggests that, although the peak windspeed may not change by much, the rainfall rate could increase dramatically as the world warms. This is a consequence of the atmosphere having to do more work to overcome the increase in static stability caused by the radiative effects of the rising greenhouse gas concentrations — and the atmosphere gets this energy by precipitating more moisture; basically, in a warmer world, the atmosphere sweats more in order to get the hurricane up to the same or slightly higher peak windspeed.

These examples provide just hints at the wide range of reasons that there is interest in getting better estimates of the changes that may occur in climatic fluctuations and extremes and in the thresholds to which society has been able to make itself resilient. If society is to make itself further resistant to fluctuations and variations — whether present levels or altered levels in the future — it is important to have improved estimates of what these levels may be. It is for this reason that those working on the U. S. National Assessment are particularly interested in the results of this Aspen Global Change Institute (AGCI) summer science session — it is climatic extremes that have the most impact on society and only by understanding them can we enhance our resilience to them.

It is climatic extremes that have the most impact on society and only by understanding them can we enhance our resilience to them.

Acknowledgments
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See *Elements of Change 1997*, Susan Joy Hassol and John Katzenberger eds., Aspen Global Change Institute, for information on the early stages of the development of this activity. See the the U. S. National Assessment Website for current information (www.nacc.usgcrp.gov).

Reference

T. R. Knutson and R. E. Tuleya, "Increased Hurricane Intensities with CO_2-Induced Warming as Simulated Using the GFDL Hurricane Prediction System," submitted to *Climate Dynamics*, July, 1998.

The Effect of Spatial and Temporal Resolution of Climate Change Scenarios on Changes in Frequencies of Temperature and Precipitation Extremes

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Under conditions of climate change, the probability of exceeding a given high temperature threshold would likely increase, and thus become less "extreme" in the statistical sense.

SESSION 2

The occurrence of climatic extremes is the main way in which human society experiences damage from climate, and it is usually the main focus of attention of the news media in reports on climate (*e. g.*, *The New York Times Magazine*, August 2, 1998). Yet we know very little about how climatic extremes may change in the future under conditions of greenhouse gas induced warming. This is largely due to the uncertainties in the ability of the major tool for investigating climate change, global climate models, to correctly simulate processes responsible for producing climatic extremes. In this paper I investigate two aspects of the uncertainty of trying to determine changes in the the frequencies of extremes with future climate change.

Through an investigation of two different spatial resolutions of climate change scenarios and through incorporation of changes in temporal variance in addition to changes in the mean of climate variables, I explore the effects of spatial and temporal resolution on the frequencies of climate extremes under climate change conditions. I also present results of validation of climate models for the reproduction of observed extremes.

In the context of this investigation I consider two different aspects, or perhaps, definitions of extremes. One is the likelihood of exceeding certain thresholds of a climate variable, known to have significant effects on a particular human resource system. These thresholds are usually also extremes from the point of view of the distribution of the climate variable. A good example of threshold extremes is high temperature extremes that affect growth of agricultural crops. For many crops (*e. g.*, corn, wheat), if certain high temperature extremes are exceeded during certain phenological stages (*e. g.*, temperatures greater than 35˚C during flowering), serious damage to the crop (particularly in final yield) can occur (Raper and Kramer, 1983). Under conditions of climate change, the probability of exceeding a given high temperature threshold would likely increase, and thus become less "extreme" in the statistical sense.

Another way of looking at extremes is to identify them statistically as an aspect of the variable distribution alone. Extremes fall in the tails of distributions. For example, for a daily precipitation extreme, this could be the value of the 90th percentile of precipitation intensity, which, depending on location, may or may not have a significant impact on human resources. However, knowledge of a large change in this quantity can still be useful in terms of how the climate is changing and can be connected to impacts further down the line. For example, the 90th percentile of daily precipitation intensity for Des Moines, Iowa in June is 25 mm/day. This means that on a rain day, there is about a 10% chance that precipitation would equal or exceed this amount. This amount (about an inch of rain) may or may not be problematic for flooding in this location. However, a change in this 90th percentile to say, 80 mm/day (more than 3 inches in one day) likely would cause major flood damage in Des Moines. Both points of view are employed in the following discussions.

Spatial Resolution

To illustrate the effect of spatial resolution I examine the output of climate change experiments from regional climate model control and doubled CO_2 runs over the central Great Plains, which have a spatial resolution of 50 km; and the results of the General Circulation Model (GCM) (control and doubled CO_2) that provided initial and lateral boundary conditions for the regional model experiments. The regional model (RegCM2) developed by Giorgi *et al.* (1993a,b) was applied to a domain encompassing the western two thirds of the continental U. S. The initial and lateral boundary conditions used to drive the regional model were provided by the Commonwealth Scientific and Industrial Organization (CSIRO) GCM, which has a horizontal resolution of 3.2˚latitude by 5.6˚longitude, equivalent to about 400 km (Watterson *et al.*, 1995). Five years of control and doubled CO_2 runs were generated. For a related project on agricultural impacts of climate change (Mearns *et al.*, 1999a), we generated a gridded climate data set made up of 11 years of daily data, covering four of the CSIRO grids in the Great Plains. The data were gridded on the 50 km scale of the RegCM grids within the larger CSIRO grids, each of which contains about 60 RegCM grid boxes (Figure 79).

Validation Over Time and Space

I first compared the observed frequency of certain extremes of temperature and precipitation with the control run of the RegCM2. For example, I examined the probability of the maximum daily temperature equaling or exceeding 35˚C. In the western part of the domain, the probability was underestimated by 0.05 to 0.15 and was overestimated in the eastern part of the domain by up to 0.15. Since the observed probabilities are relatively small to begin with, some of these errors are relatively large from the point of view of percentage error. These errors are reflected partially in the errors in mean maximum temperature. The model underestimates the mean maximum temperature over about 55% of the domain, and overestimates it over about 45%. However, a greater proportion of the domain showed errors of overestimating the probability of the extreme than underestimating it (60% compared to 40%). The contrast in these relative percentages can be explained by looking at the error in daily variance which affects the calculation of the probability of the extreme. In July, the model in general overestimates the daily variance of temperature, and thus produces too many extremes, even when the error in the mean is very small or even an underestimation. Such contrasts can also be demonstrated for precipitation.

The model underestimates the mean maximum temperature over about 55% of the domain, and overestimates it over about 45%.

The use of differences and ratios for temperature and precipitation, respectively, is the classic manner in which changed climate data sets have been developed for use as input to impact models, such as crop models.

SESSION 2

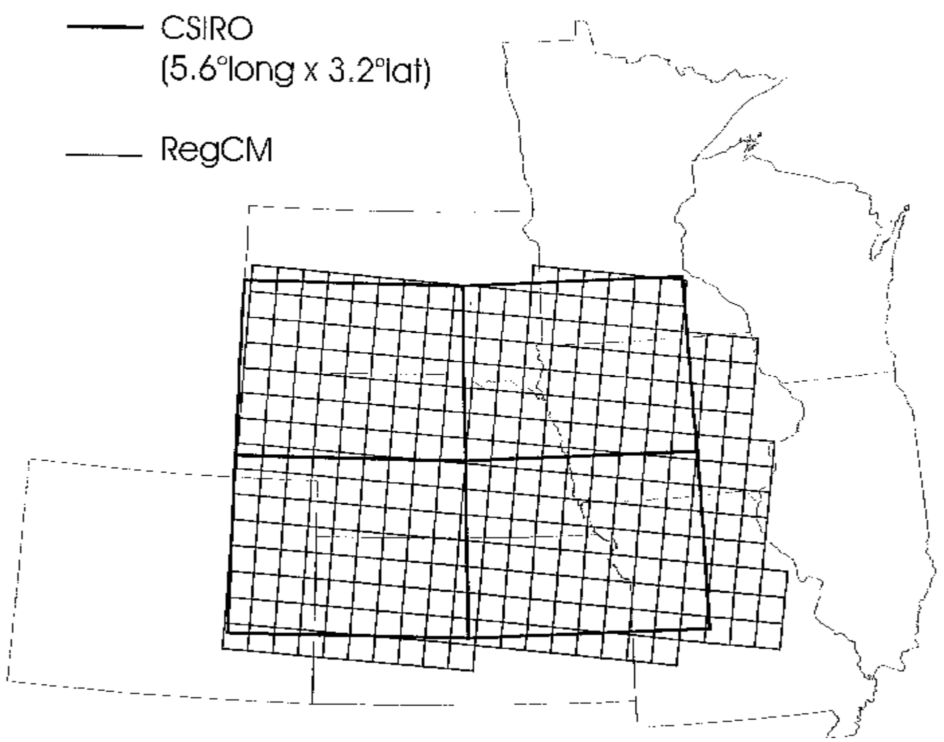

Figure 79
CSIRO GCM ~400 km grids (heavy line) and RegCM 50 km grids in the U. S. Great Plains. Each CSIRO grid box contains about 60 RegCM grid boxes.

I then produced climate change data sets on two different spatial resolutions. These two different scenarios were formed by adding monthly differences (doubled CO_2 run compared to the control run) in temperature or ratios of precipitation, to the observed daily data. In one set, the changes in climate resolved at the RegCM scale were added, and in the other the changes from the coarser grid CSIRO. Thus, in the southeast CSIRO grid box, for example, in the coarse resolution scenario, the same monthly changes are appended to the observed data at each RegCM scale; in the fine resolution case, a different set of changes are added to each RegCM grid box. It should be noted that for temperature, the changes in the data sets are very straight forward. For a mean temperature increase of 3°C, for example, 3° are added to each daily observed value. This changes the mean of the observed time series, but has no effect on the variance of the time series. With precipitation, the situation is quite different. A ratio of $2xCO_2$ to control run precipitation is applied to the daily values of precipitation. This has the effect of changing the mean by that ratio, but also changes the variance of the intensity of precipitation by the ratio squared. No change in the frequency of precipitation occurs. The use of differences and ratios for temperature and precipitation, respectively, is the classic manner in which changed climate data sets have been developed for use as input to impact models, such as crop models.

Change in Temperature Extremes

In both the CSIRO and RegCM2 changed data, the increased frequency of the extreme event was very pronounced. Across the domain, in the observed case, the probabilities range from 0.0 to 0.35. In the climate change cases, the probabilities range from 0.3 to 0.95. This large increase in the probabilities of extremes when the increase in the mean was only about 3˚C, is a feature of the nonlinear relationship between means and extremes (Mearns *et al.*, 1984); that is to say, that a relatively small increase in the mean results in a relatively large increase in the frequency of extremes. There was not, however, much difference in the distribution of the extremes based on the scale of the climate change scenario. This reflects the fact that temperature distribution over space is a relatively smooth field.

Change in Precipitation Extremes

For precipitation we examined changes in the 90th percentile of precipitation intensity, between the observed and the two scales of climate changes. In April, for example, the 90th percentile of the observed precipitation ranged from 10 to 35 mm/day across the spatial domain. In both climate change cases, precipitation generally increased, but the pattern of the change in extremes is quite different between the two. The CSIRO climate change resulted in a much larger increase in the 90th percentile in the southern parts of the domain (to over 50 mm/day) than did the changes from the RegCM2, which were on average 25 mm/day. Also, the RegCM2 climate changes were more heterogeneous across space. Changes in the spatial distribution of extremes could have important implications for the impacts of extreme events. These differences follow largely from differences in the changes in mean precipitation between the two scenarios, which are discussed in Giorgi *et al.* (1998) and Mearns *et al.* (1999b); but again, the differences in extremes are more substantial than those for the means. Note also that the means of altering the observed precipitation data sets exaggerates changes in extremes, since no change in the frequency of precipitation is taken into account.

Temporal Resolution

By the effect of temporal resolution, I am referring to the effect of not only changes in the mean of a variable, but also changes in the higher order moments, *e. g.*, the variance. Changes in variance are very important in determining the changes in the frequencies of extremes. As Katz and Brown (1992) demonstrated, changes in the variance of a time series has a larger effect on changes in the frequencies of extremes than does the change in the mean of that series. To demonstrate the importance of change in variance, I altered time series according to the mean changes only determined from the climate change scenarios calculated from the Regional Climate Model described above, and then also according to changes in both the mean and variance and then calculated the changes in the frequency of certain extremes, such as the probability of the maximum temperature equaling or exceeding 37.8˚C on any day during the summer months. Changes in means and variance were accomplished by altering the parameters of a stochastic weather generator (Mearns *et al.*, 1997).

For this set of regional climate runs, there were some very distinctive changes in the daily variance of temperature. Variance largely decreased substantially in winter months, and increased in summer months. This seasonal pattern of change in variance of daily tempera-

This large increase in the probabilities of extremes when the increase in the mean was only about 3˚C, is a feature of the nonlinear relationship between means and extremes.

ture has been found in a number of regional and global model runs with increased greenhouse gases, in mid-latitude regions (Gregory and Mitchell, 1995; Mearns *et al.*, 1995, 1999b; Boer *et al.*, 1999). I provide one typical example from a grid box in Iowa. For the grid box that corresponded with the location of Des Moines, Iowa, I calculated that probability for the two different changed data sets. For July, for example, the observed probability was about 0.02. With the mean changed climate it was 0.2 (an order of magnitude higher), but with the addition of the change in variance, this probability increased further to 0.27. In this case, the change in the mean more strongly affected the change in probability because the relative change in the mean was much larger than the change in the standard deviation. The mean increased by 4.4˚C and the standard deviation by 1.7˚C.

In the case of precipitation, the changes that occur in the characteristics of the observed data sets when combined with the climate changes, are more complex than for temperature. It is often (although not always) the case that the classic mean change method exaggerates the change in the extremes of precipitation intensity, since only change in intensity (and not occurrence) is taken into consideration. When stochastically generating the changed precipitation time series, changes in both mean and variance of intensity and the probability of precipitation can be taken into account. For example, for the Des Moines location, I generated the changes again for the summer months. In August, for example, the observed 90th percentile is 27.8 mm, with the mean change only 75.3 mm, and with the mean and variance change 63.3 mm. With the variance change included, the value returns to something likely more reasonable. This is because the frequency of precipitation increases in the case of the variance change, and although the intensity increases, it doesn't increase as much as in the mean change case.

The effect of spatial resolution of climate change scenarios may have a greater effect on the determination of extremes in daily precipitation than in extremes of daily temperature.

In the case of precipitation, the contrast I present is more like two ways of changing higher order moments, rather than a mean change only versus mean plus variance change. However, I pose it in the latter manner because this again is how the ratio approach has been described, as producing a mean change alone.

Summary and Conclusions

To summarize, in the cases of validating climate models for reproduction of extreme events, the errors in reproduction of extremes can be decomposed into errors in the reproduction of the mean, variance, and other higher order moments (*e. g.*, skewness) of the distribution. The effect of spatial resolution of climate change scenarios may have a greater effect on the determination of extremes in daily precipitation than in extremes of daily temperature. This follows from the greater spatial variability of precipitation. And finally changes in higher order moments (*e. g.*, variance) contribute importantly to changes in the frequency of extremes. To not consider these changes in construction of climate change scenarios could lead to serious under or overestimates of extremes.

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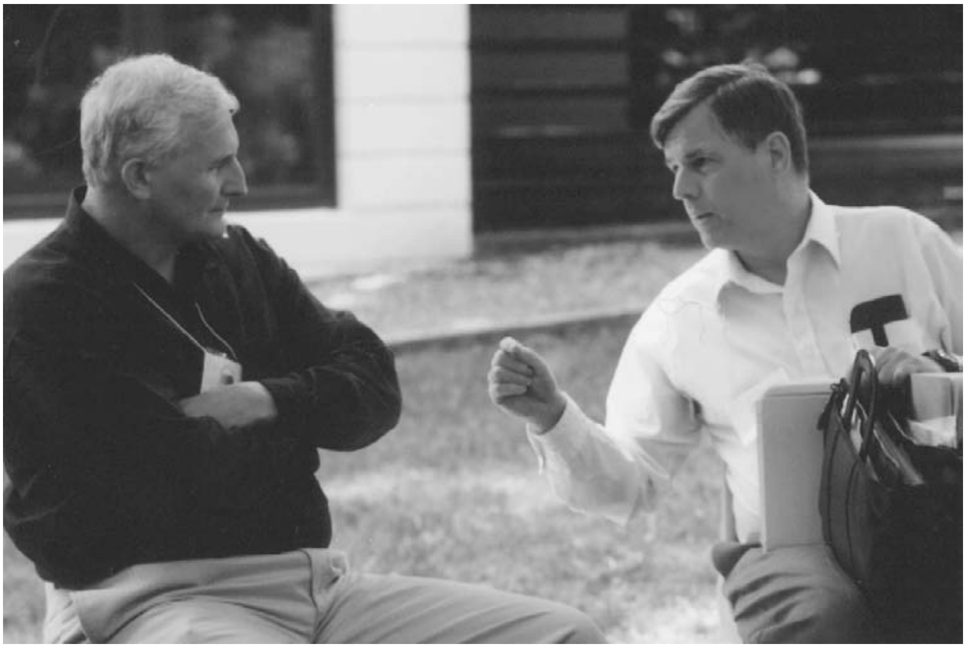
In both the CSIRO and RegCM2 changed data, the increased frequency of the extreme event was very pronounced.

Linda Mearns discusses how model resolution affects the portrayal of climate extremes.



Toni Socci and Rick Sylves discuss sociopolitical aspects of climate extremes.

Jerry Meehl leads a working group on impacts of climate extremes.

Climate Anomalies Associated with Future El Niño Events

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Climate extremes associated with El Niño events have been shown to significantly affect society in many locations of the world. For example, extremes associated with El Niño events in the past have included droughts in India, South Africa, Southeast Asia, Australia, and Micronesia; torrential rainfall in equatorial eastern Africa and the central and eastern equatorial Pacific including coastal Ecuador and Peru; and cool and wet conditions across the southern tier of states in the U. S. (*e. g.*, see Ropelewski and Halpert, 1987).

When discussing possible future changes of climate extremes associated with El Niño events, there are a number of factors that affect the manifestation of El Niño effects. For example, a number of studies have shown that observations of sea surface temperatures (SSTs) since World War II are characterized by an "El Niño-like" pattern on the decadal timescale (*e. g.* Zhang *et al.*, 1997; Lau and Weng, 1998; Meehl *et al.*, 1998). Thus, the El Niño pattern familiar on the interannual timescale, with warmer SST anomalies in the central and eastern equatorial Pacific than in the far western Pacific with associated eastward shifts of heavy precipitation, is seen in a similar form on the decadal (9-20 year) timescale. There has also been a long term trend in the observed SSTs since WW II that has an El Niño-like pattern (Lau and Weng, 1998). Additionally, future climate experiments with global coupled climate models with increased CO_2 have shown an El Niño-like pattern solely as a mean climate system response to those increases of CO_2 (*e. g.*, Meehl and Washington, 1996; Timmermann *et al.*, 1998). Thus, the El Niño-like pattern seems to be a fundamental response of the climate system on a number of different timescales and from several different forcings. This complicates considerably an assessment of climate affects associated with future El Niño events.

The El Niño-like pattern seems to be a fundamental response of the climate system on a number of different timescales and from several different forcings.

There are other difficulties as well. An El Niño "event" is defined in relation to some long term mean climate average. If the climate is non-stationary, that is, if the mean climate is slowly changing, there are problems with evaluating a future El Niño event in relation to some mean climate state that may not be the same as present (Meehl *et al.*, 1993). Thus, is it better to assess effects of future El Niño events in relation to the present-day mean, or in relation to the future mean climate? Here we examine present-day El Niño simulated by a global coupled climate model, and then look at future El Niño events in a climate where there has been an increase in CO_2 and sulfate aerosols. We show El Niño anomalies for present-day events in relation to present-day mean climate, and future El Niño anomalies in relation to future mean climate. Then we perform differences of those anomalies (and

thereby remove the mean climate change) to show changes in future El Niño anomalies compared to today's El Niño anomalies.

The global coupled climate model has an R15 atmosphere (roughly 4.5 degrees latitude by 7.5 degrees longitude) with 9 levels in the vertical. The dynamical global ocean component has 1 degree by 1 degree horizontal resolution with 20 levels in the vertical. Sea ice is simulated with both dynamical and thermodynamical formulations. There are *no* corrections to the fluxes of heat, momentum or fresh water (referred to as flux corrections or flux adjustments) between the atmosphere and ocean components. A description of the model is given in Meehl and Washington (1995).

The climate model is able to represent the two timescales of El Niño-like variability mentioned above (interannual and decadal), with somewhat reduced amplitude (Meehl *et al.*, 1998). The experiments analyzed here are from a 75-year period in the control run with constant present-day CO_2 amounts, and from a future climate change experiment from 1995 to 2035. The concentrations of CO_2 and sulfate aerosols were first added as observed and the model was run with those concentrations from the period 1900 to 1995. After 1995, CO_2 was increased at 1% per year and sulfate aerosols increased regionally as described by Mitchell *et al.* (1995). By the year 2035, the globally averaged temperatures warmed over 2˚C compared to the pre-industrial (around the year 1900) values in the model, while the SSTs in the tropical Pacific have warmed more in the eastern equatorial Pacific (nearly 3˚C) compared to the western Pacific (about 1.5˚C) (Meehl *et al.*, 1998). This change in future climate base state due solely to the changes in anthropogenic forcing also includes a deepened Aleutian low pressure center, lower pressure over the eastern tropical Pacific, a deeper south Pacific trough, and higher pressure over tropical Australasia.

Present-day El Niños are characterized by many of the same features listed above for the change in base state for the future climate.

Present-day El Niños are characterized by many of the same features listed above for the change in base state for the future climate (Meehl and Arblaster, 1998). Therefore, in comparing the simulated present-day El Niños from the model (defined here as area-averaged monthly SST anomalies in the Niño3 region — 90˚W-150˚W, 5˚N-5˚S — above 0.5˚C for the first year or remaining above 0.5˚C for a full year going from May to the following May; 10 El Niño events in the 75 years of control run are analyzed) there are positive SST anomalies in the central and eastern equatorial Pacific, positive precipitation anomalies in the central equatorial Pacific and negative precipitation anomalies over Australasia (Figure 80, shown for December-January-February [DJF] midway through a composite El Niño event).

Future El Niño events are taken from the future climate change experiment with increasing CO_2 and sulfate aerosols for the period 2005-2035. For that period, monthly Niño3 SST anomalies are detrended and 5 El Niño events are chosen as defined above. Anomalies for the composite events are computed relative to the mean climatology for the period 2005-2035 and shown in Figure 81 for the comparable DJF season as in the present-day El Niños in Figure 80. Similar features to those noted above for the present-day events in Figure 80 are evident for the future El Niño events in Figure 81.

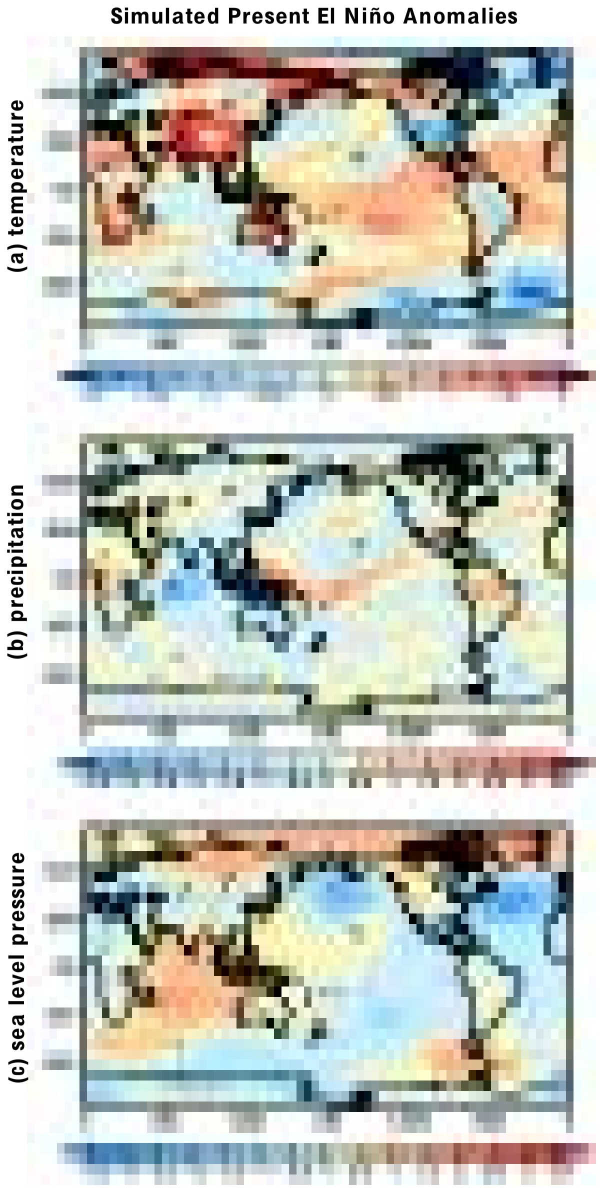

Figure 80
Composite anomalies for 10 El Niño events from the climate model control run, DJF midway through an average event, for a) temperature, b) precipitation, and c) sea level pressure.

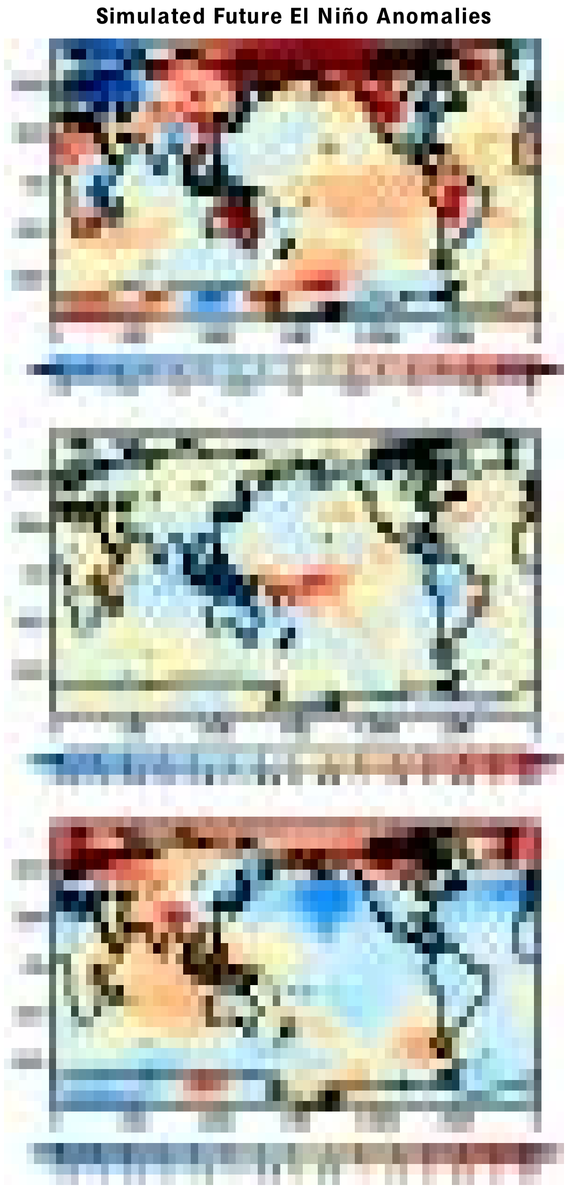

Figure 81
Composite anomalies for 5 El Niño events from the future climate experiment with increased CO_2 and sulfate aerosols, taken from the period 2005-2035, DJF midway through an average event.

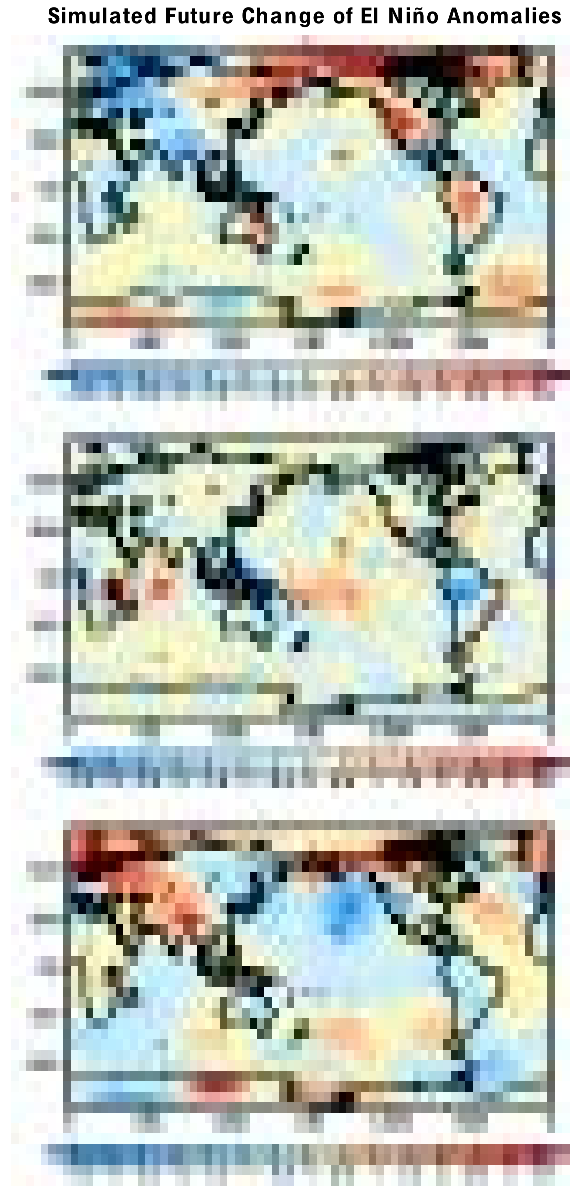

Figure 82
Difference of El Niño anomalies, future El Niño events minus present El Niño events, DJF, for a) temperature, b) precipitation, and c) sea level pressure.

To examine the change in El Niño climate anomalies in the future climate compared to the present climate, we compute the difference, future El Niño anomalies minus present El Niño anomalies, and plot those differences in Figure 82. The amplitude of changes in SST anomalies in the tropics is on the order of only a few tenths of a degree in Figure 82a (indicating that the size of El Niño events in the future is not much different from today), but there is an apparent enhancement of precipitation anomalies in the tropical Indian and Pacific regions. That is, there are anomalously drier areas in future El Niño events over Australasia, and anomalously wetter areas over the central Pacific. These are in areas already affected with precipitation extremes with those signs in present day events (Figure 80). In future El Niño events in the tropical Indian and Pacific regions, anomalously dry areas get drier, and anomalously wet areas get wetter. There is an intensification of precipitation extremes in future El Niño events in those regions. This has been noted to occur due to the warmer mean SSTs in the future climate and the nonlinear relationship between surface temperature and evaporation (Meehl *et al.*, 1993).

The change in teleconnection pattern over the North Pacific and North America also bears noting in the SLP plot in Figure 82c. The Aleutian low in the North Pacific is intensified and shifted southward in the future El Niño events (as indicated by the negative SLP differences in Figure 82c west of Canada, and comparing the southward shift in the maximum negative SLP anomalies in the future events in Figure 81c compared to the present events in Figure 80c in the North Pacific region). This shift of the SLP anomalies there has consequences for the precipitation and temperature extremes associated with El Niño events over North America. In the future events, the anomalously warm surface temperatures over Canada in Figure 80a shift southward over the western U. S. in Figure 81a, while the anomalously wet conditions over most or southern North America in present events in Figure 80b weaken in the future events in Figure 81b.

This southward shift of the anomalous low pressure in the North Pacific has been shown to be associated with the changed base state of the climate in the Northern Hemisphere (Meehl *et al.*, 1993). That is, with the increase of precipitation in the future climate over the tropical Pacific, the Rossby wave response in the northern midlatitudes causes a mean change in the longwave pattern in the future climate. When the anomalous convective heating in the central Pacific during an El Niño event is superimposed on that changed base state in the future climate, the Rossby wave response is modified such that the Aleutian low is intensified somewhat further south than in present-day El Niño events. This then changes the climate extremes accordingly over North America.

In future El Niño events in the tropical Indian and Pacific regions, anomalously dry areas get drier, and anomalously wet areas get wetter. There is an intensification of precipitation extremes in future El Niño events in those regions.

Summary

The manifestation of climate extremes associated with El Niño events is affected by interannual, decadal and longer (trend) timescales, all with similar spatial features (“El Niño-like”). Assessment of effects of future El Niño events is further complicated by changes of mean climate. That is, an “event” is defined as an anomaly in relation to some mean state, and when the mean state is changing, it confuses how to define the climate effects associated with such “events”. Changes in future frequency and magnitude of El Niño events is difficult to quantify without ensembles of climate change scenario experiments. However, due to an anticipated warmer mean climate in the future due mainly to an increase of CO_2, climate

model results show that a given El Niño, superimposed on the warmer mean climate state, will likely be associated with intensified tropical Indian and Pacific precipitation anomalies (anomalously wet areas in present-day events get wetter in future El Niños, and anomalously dry areas become drier), with some shifts in extratropical teleconnections over the North Pacific and North America.

Climate model results show that a given El Niño, superimposed on the warmer mean climate state, will likely be associated with intensified tropical Indian and Pacific precipitation anomalies, with some shifts in extratropical teleconnections over the North Pacific and North America.

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Global Warming and Species Movement: The Case of Butterflies

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One of the least controversial predicted responses to a global climatic warming trend is that species will shift their ranges poleward and upward in altitude. Mean global temperatures have risen significantly this century (see *e. g.*, IPCC 1995, 1998). Relatively sedentary organisms like butterflies are a good choice for tracking long term trends in wildlife range shifts in response to climatic warming. Most butterflies live in one population for many generations. A range shift northward is a process which takes decades. As climatic shifts make the most southern regions less suitable and the far northern regions more suitable, butterfly populations at the southern end of the range go extinct while new populations are created northward of the previous boundary.

Good evidence for recent range shifts has been studied for Edith's Checkerspot butterfly (*Euphydryas editha*) in western North America (Parmesan 1996). This particular species was chosen because numerous independent studies have shown *E. editha* to be very sensitive to climate: subtle micro-climatic influences (such as slope aspect) affect population growth and stability, and populations have been observed to go extinct following extreme climatic events (Singer and Thomas 1996, Thomas *et al.* 1996, Weiss *et al.* 1988, Ehrlich *et al.* 1980, Singer and Ehrlich 1979).

By determining where population extinctions had occurred, the mean location of populations of Edith's Checkerspot butterfly was found to have shifted northward by 92 km and upward by 124 meters since the beginning of the century (Figure 83). In the same geographic area as this species range, analyses of climatic records covering the same time frame show that climatic isotherms have shifted northward by 105 km and upward by 105 meters (Karl *et al.* 1996). Further, the altitudinal cline in frequency of population extinction had a breakpoint at 2,400 meters, with the trend being for lowered extinction rates at the highest elevations (Figure 84). This breakpoint correlated to that for trends in snowpack depth and timing of snowmelt, with significant trends towards increased depth and later melt-date above 2,400 meters, and the opposite trends below 2,400 m (Johnson 1998).

Human alteration of the landscape is also known to be a major driver of changes in modern species' distributions. Though the Edith's Checkerspot study was observational, it focused on responses to climate change by controlling for habitat degradation: only sites which were still suitable habitat were selected, whether or not *E. editha* still existed. An analysis of more general habitat destruction over the species' range showed that loss of habitat in the surrounding region was uncorrelated with the natural latitudinal and altitudinal clines in popu-

The mean location of populations of Edith's Checkerspot butterfly was found to have shifted northward by 92 km and upward by 124 meters since the beginning of the century.

lation extinction. Therefore, habitat destruction has neither overtly nor covertly influenced the northward and upward range shift found (Parmesan, unpublished).

This study focused on responses to climate change by controlling for habitat degradation: only sites which were still suitable habitat were selected.

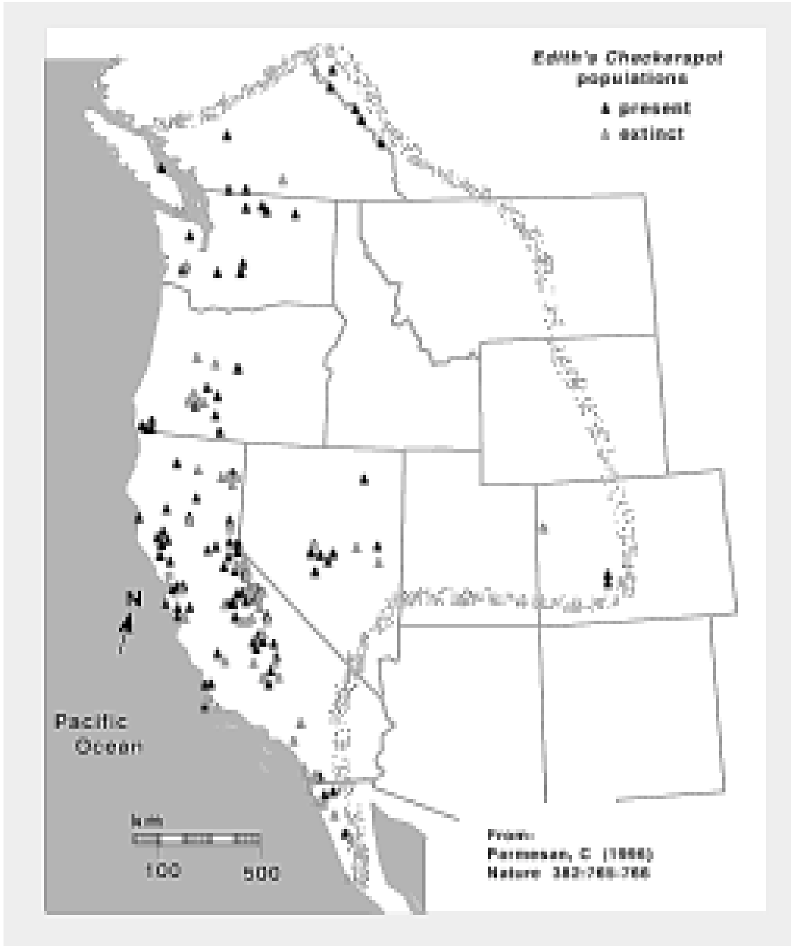

Figure 83
The mean location of populations of Edith's Checkerspot butterfly has shifted northward by 92 km and upward by 124 meters since the beginning of the century.

Although these two large patterns of change match in magnitude, claims that regional climatic warming has caused the range shift of *E. editha* can be criticized on two grounds: 1) the data are correlation and so the match in trends could be coincidence, and 2) Edith's Checkerspot is known to be extremely climatically sensitive and so may not be representative of responses of other butterfly species, or of wildlife in general, to the current global warming trend. Since the global warming trend is increasingly being seen as due to human greenhouse gas production and therefore likely to continue, it is of great importance to know whether either of these criticisms are valid.

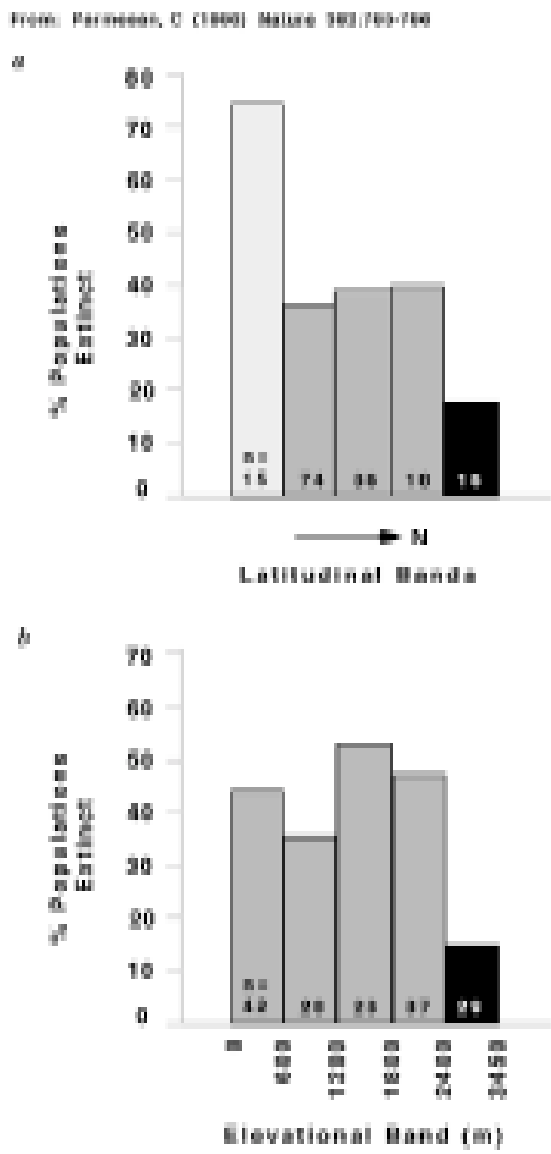

Figure 84
The altitudinal cline in frequency of Checkerspot population extinction had a breakpoint at 2,400 meters, with the trend being for lowered extinction rates at the highest elevations.

To answer these criticisms, we are in the process of replicating this study with other species and other geographic regions. Europe has a strong history of butterfly collecting and so has good data sets and modern monitoring schemes. Europe has experienced a mean warming trend of 0.36°C, along with increased cloudiness, a reduction in the diurnal temperature range (DTR), and an increase in precipitation in the North. We have studied distributions of up to 32 butterfly species in northern and southern regions of Europe and found that, overall, 80% have shifted their ranges northward and/or upward. There is a greater ten-

We have also studied distributions of up to 32 butterfly species in northern and southern regions of Europe and found that, overall, 80% have shifted their ranges northward and/or upward.

dency for movement at the northern edges than at the southern edges. This difference is consistent with the differences in climatic warming these two regions have experienced: warming has been more pronounced in the northern countries (IPCC 1998, European workshop on climate change 1994, Finnish report 1996). This greater stability at the southern edge may also be due to the greater topographic diversity of the region; even if species were responding to a climate signal, they wouldn't have far to move because they could simply shift from a south-facing slope to a north-facing slope. Data indicate that the butterfly species are moving by 50-100 km, which is in line with the ~0.4°C observed warming.

It is also important to point out that it is not simply mean climate warming but changes in extreme events that are important to wild plant and animal life. Flight seasons for butterflies occur in Spring and Summer and last 4-6 weeks. The total active period of each species begins 4-8 weeks before flight season and contiunues for 4-6 weeks after flight season. Shifts in mean temperature and frequency of extreme climatic events that take place during this growing season have significant effects. It is also possible that trends towards warmer winters may also stress insects in hibernation by causing them to increase their metabolic rates at a time of the year when no food is available: in other words, warm winters can cause starvation. Ecologists require better daily data on extremes during the growing season of indicator species, as well as better data on sequences of weather events — combinations of one extreme event followed by another. For instance, among plant and animal populations, one extreme day (*e. g.* very high maximum temperature) may be tolerated, but four extreme days in a row are likely to cause large population crashes, or even local extinctions.

Data indicate that the butterfly species are moving by 50-100 km, which is in line with the ~0.4°C observed warming.

A final point is that options for species migration are becoming more limited by human land use change. For example, the best habitat for the southern race of *E. editha*, (the Quino Checkerspot), lies in Mexico, but 80% of the populations there have gone extinct. Habitats just to the north in southern California, which theoretically they could move into, have been destroyed by urbanization. Thus, the combination of land use change and climate change is causing significant problems, particularly for endangered species and subspecies that are already habitat-limited.

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The combination of land use change and climate change is causing significant problems, particularly for endangered species and subspecies that are already habitat-limited.

Trends in Flood and Hurricane Impacts in the U. S. — A Selected Review of Recent Research

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The impacts of extreme weather events are of growing interest to decision makers. One reason for this interest is growth in the absolute amounts of climate damage in recent decades. Some have speculated that growing damages are the result of climate changes, while others speculate to a growth in societal vulnerability. Recent work at the Environmental and Societal Impacts Group at the National Center for Atmospheric Research has sought to understand the factors underlying trends in impacts. This paper reviews some of this recent work in the context of flood and hurricane impacts in the U. S.

In the case of economic damages associated with floods and hurricanes, there is a trend of increasing losses in recent decades in the U. S.

"We do not know... for sure that the warming of the Earth is responsible for what seems to be a substantial increase in highly disruptive weather events, but many people believe that it is, and that we have to keep looking into it... If there is a larger cause which can be eased in the future, we ought to go after that solution as well." – President Bill Clinton, April 22, 1997

This statement by President Bill Clinton reflects two common perceptions. First, it reflects a sense that the economic impacts associated with extreme weather events have increased in recent years. Second, a perception exists that the recent increase in weather-related events is due to changes in climate related to global warming. In recent years, these perceptions have resulted in almost every extreme event being attributed, by someone, to global warming.

The perceptions are more than simply idle speculations — they underlie policy decisions with important social, economic and political ramifications. For instance, in December of 1997 representatives from nations around the world met in Kyoto, Japan to discuss and debate implementation of the Framework Convention on Climate Change. Because policy is based on the perceptions that policymakers hold about climate, it is worth determining the validity of the two perceptions.

In the case of economic damages associated with floods and hurricanes, there is a trend of increasing losses in recent decades in the U. S. Thus, the first perception is demonstrably valid. There is, however, little reliable evidence to date to support the perception that recent trends in economic losses in the U. S. are largely attributable to changes in climate. Clearly, climate has varied regionally with respect to particular phenomena, however, this variation is difficult to discern in the historical record of societal impacts (e. g., dollar losses). Instead,

the strongest signal present in the historical record is that increased societal vulnerability is the primary cause of recent increases in documented economic losses. Note that this finding in no way refutes the global warming hypothesis. Rather, it refutes the claim that the growth in losses can be largely attributed to the increased frequency or magnitude of hurricanes or precipitation. This is consistent with the findings of the Intergovernmental Panel on Climate Change, published in 1996.

This review discusses trends in data on flood and hurricane impacts in the U. S. and recent research seeking to link these trends with climate and societal information. Arguably, hurricanes and floods are the two phenomena that societal impacts researchers best understand from the standpoint of trends and impacts.

Floods

When climatologists discuss floods, they typically are referring to hydrologic floods; but when policymakers discuss floods, they are typically referring to damaging floods. This situation is problematic as hydrologic floods are not well correlated with damaging floods. The poor relationship between what climatologists, hydrologists, and other physical scientists call floods and those floods which actually cause damage, has limited what can be reliably said about the causes of observed trends in damaging floods. To focus research on the societal impacts of floods, this paper defines a damaging flood as a flood in which society suffers losses related to the event.

By any measure, floods have a significant impact on society. The Red Cross estimates that over the 25-year period ending in 1995, more than 1.5 billion people worldwide have felt the impact of floods. Of that total, more than 318,000 people were killed and more than 81 million were made homeless. In addition, over the period 1991-1995, flood-related damages totaled more than US$ 200 billion (not inflation adjusted) worldwide, representing close to 40% of all economic damages attributed to natural disasters over the period.

While recent research has focused on developing a better quantitative understanding of extreme weather impacts related to the inter-relationship of atmosphere and society in the context of hurricanes and other extreme events, an understanding of floods has remained elusive. Reliable and accurate knowledge of the science of floods climatology, hydrology and meteorology is important because it plays a role in many policy decisions, including land use, insurance, and the allocation of scarce public resources. Yet, in spite of the large and growing impacts of floods on society, most discussion of the science and policy of floods is characterized by unexamined assumptions and imprecise language — not a recipe for the translation of science into effective policies.

An example of this can be found in recent discussion about climate and floods. Recent research has found that "the proportion of total precipitation derived from extreme precipitation events reflects large increases in such events during the warm season over the United States" (Karl et al. 1995). This has been popularized as "increasingly, when it rains, it pours" and has led to conclusions such as the following, presented in *The New York Times* in 1997: "heavy rainstorms have become more common, making damaging floods more likely" (Stevens 1997). Such conclusions have been repeated by government officials, scientists,

The strongest signal present in the historical record is that increased societal vulnerability is the primary cause of recent increases in documented economic losses.

and the media. However, a closer inspection of the data shows that the measure of "extreme precipitation" used in the Karl et al. 1995 study (a 2-inch rainfall threshold) is not well related to the flood damage record in the U. S.

Other factors related to damaging floods include population, development and federal policies. Empirical evidence from a number of cases clearly shows that climate, population growth and development, and policy each play a role in trends in damaging flooding in the U. S., but the state of knowledge is such that the relative contribution of each factor is poorly understood.

At first blush, one might be tempted to assert what seems obvious: precipitation (*i. e.*, rain or snow) causes damaging floods. But the relationship between precipitation and damage is a complex one, particularly when one aggregates precipitation and flood damage over more than a single drainage basin. The relation between precipitation and damages is shaped by countless intervening factors such as land use, river channel modifications, structural and non-structural mitigation measures, etc. Consequently, in almost all cases, a damaging flood results from a combination of physical and societal processes. Losses would not occur without the presence of the flood waters, and similarly, human occupancy of the floodplain. Therefore, to understand the causes of damaging floods requires knowledge of the interrelated physical and societal factors which underlie the physical and societal processes.

Climate, population growth and development, and policy each play a role in trends in damaging flooding in the U. S., but the state of knowledge is such that the relative contribution of each factor is poorly understood.

A national flood damage record is kept by the National Weather Service for the period 1903-present, and state level data 1983-present. The reported losses are for "significant flood events" and include only direct damages due to flooding that results from rainfall and/or snowmelt. (Flooding due to winds, such as coastal flooding from storm surges, is not included.) The annual losses are based on "water years," October to September. The database can certainly be improved, but for present purposes, the Federal Emergency Management Agency has concluded that the dataset can be used for trend analysis.

At the national level, ten precipitation-related measures were selected:

(1) total precipitation (USKPR)
(2) number of wet days per station (USWET)
(3) number of extreme precipitation days (>2 inches) per station (USEXT)
(4) number of 2-day heavy precipitation events per station (USHP2)
(5) number of 3-day heavy precipitation events per station (USHP3)
(6) number of 5-day heavy precipitation events per station (USHP5)
(7) number of 7-day heavy precipitation events per station (USHP7)
(8) percentage of the conterminous U. S. area with much above normal cold season (Oct.-April) precipitation (HPCOLD)
(9) percentage of the conterminous U. S. area with the number of wet days much above normal (ABNWET)
(10) percentage of the conterminous U. S. area with much above normal proportion of total annual precipitation from 1-day extreme events (ABNEXT)

Measures (1)-(7) were obtained from Illinois State Water Survey. Methods used to compute the partial-duration time series for measures (4)-(7) are described in Kunkel et al. (1996).

Note that thresholds for measures (2), (3) and (9) are based on absolute levels of daily precipitation (greater than 1 or 2 inches). In contrast, the thresholds for measures (4)-(8) and (10) are based on precipitation which is usually high compared to normal amounts at each weather station. In measures (4)-(7) the threshold for "heavy precipitation" is based on a 5-year recurrence interval, that is, the threshold for a specific station is the N-day precipitation amount that is exceeded on average once every five years (for N=2, 3, 5, or 7, respectively). In measure (8), "much above normal" is defined as being within the upper 10% of all cold season values at a given station. In measure (10), 1-day extreme events are defined as those in the upper 10% of daily precipitation amounts at a given station. The analysis is confined to 1932-1997 because of data limitations.

Person product-moment correlation coefficients are used to test for a linear relationship between pairs of variables. Frequency distributions of each data series were tested for normality and, if necessary, transformed to best approximate a normal distribution. Most of the data series were found to contain statistically significant increasing trends over time. As a first step, correlations were computed between the original data series. Then, linear trends were removed using simple linear regression and correlations were computed again using the detrended series.

The flood damage data were converted to a normal distribution by the use of a log transformation. Precipitation measures (1)-(7) and (10) do not deviate significantly from normality, based on the Shapiro-Wilk test. However, measure (8) required a log transformation, and measure (9) required a square root transformation.

The relationship of damage, D, with the ten precipitation-related measures is displayed in Table 15. The second column shows the original correlations, and the third column shows the correlations after the linear trend has been removed from each variable. Although the correlations are reduced somewhat after detrending, all measures except (3), (8) and (9), are significantly related to D. In both columns, D is shown to be most highly correlated with 2-day and 5-day heavy precipitation events.

Table 15

Variable Name	Correlation	Correlation After Detrending	Variance Explained
USKPR	0.477*	0.381*	14.5%
USWET	0.484*	0.353*	12.5%
USEXT	0.354*	0.267	—
USHP2	0.507*	0.424*	18.0%
USHP3	0.441*	0.358*	12.8%
USHP5	0.495*	0.419*	17.6%
USHP7	0.425*	0.352*	12.4%
HPCOLD	0.305	0.221	—
ABNWET	0.340*	0.308	—
ABNEXT	0.457*	0.350*	12.3%

*significantly different from zero (α = 0.01)

In almost all cases, a damaging flood results from a combination of physical and societal processes. Losses would not occur without the presence of the flood waters, and similarly, human occupancy of the floodplain.

The coefficient of variation is commonly used to estimate the proportion of variance that is explained by a predictor. The last column of Table 15 shows the percentage of variance in D explained by each predictor, after detrending. These figures indicate that, after linear trends are removed, the number of 2-day heavy precipitation events per station (measure (4)) explains 18% of the variance in D, while total precipitation (measure (1)) is somewhat less strongly related to D, explaining 14.4% of the variance. Multiple regressions combining other predictors with measure (4) show that none of the other predictors significantly improve the model fit achieved with measure (4) alone.

It has been suggested that "intense precipitation" or "heavy downpours" are most likely to lead to floods. But how should "intense" or "heavy" rainfall be defined? Should it be based on an absolute amount of rainfall, as in measure (3), or an amount relative to normal rainfall levels in a given area? Our results indicate that measure (3), based on a fixed threshold of 2 or more inches of rainfall, is not well related to flood damage. The measures which are most strongly related to flood damage, *i. e.*, the 2-day and 5-day heavy precipitation events, are defined relative to historical rainfall at each station. This suggests that flood damage may be more influenced by short-term rainfall amounts that are relatively high compared to an average for a given area, as compared to rainfall amounts exceeding a fixed threshold. A great deal of unexplained variance remains. Local factors, both social and weather-related, must be taken into account in explaining the damages inflicted by floods. The reader is urged to exercise caution in the interpretation of this analysis as it is preliminary. Further information can be found in Pielke *et al.* (1999).

Flood damage may be more influenced by short-term rainfall amounts that are relatively high compared to an average for a given area, as compared to rainfall amounts exceeding a fixed threshold.

Hurricanes

A fundamental problem in understanding hurricane losses is that historical losses at different points in time are not comparable because the underlying social conditions have changes. For example, it is meaningless to compare the losses associated with the devastating 1926 Great Miami Hurricane with those related to Hurricane Andrew in 1992. Even after adjusting for inflation, Miami is a far different place in 1992 than in 1926. Even the Miami of 1999 is not directly comparable to that of 1992.

Normalization methods provide a means to place historical losses on a comparable basis. The following description is based on normalized hurricane losses from Pielke and Landsea (1998). In principle, a similar methodology could be applied to any time series of catastrophes.

To normalize past hurricane losses to a base year's values, it is assumed that losses are proportional to three factors: inflation, wealth and population. Of course, it is possible that these factors would be replaced and/or complemented by others which represent changes to the insurance industry (*e. g.,* changes in deductibles, policy types, etc.). The result of normalizing the data will be to produce the estimated impact of any storm as if it had made landfall in (this case) 1995.

Inflation is accounted for using the implicit price deflator for Gross National Product, as reported in the Economic Report of the President. Wealth is measured using an economic statistic kept by the U. S. Bureau of Economic Analysis called "Fixed Reproducible Tangible

Wealth" and includes equipment and structures owned by private business, owner-occupied housing, nonprofit institutions, durable goods owned by consumers, as well as government-owned equipment and structures. Wealth is accounted for in the normalization using a ratio (inflation-adjusted) of today's wealth to that of past years (end of year gross stock). Because the measure of wealth is based on national figures, we have adjusted it back to per capita by removing from it the relative changes in the entire U. S. population. Wealth data are available from 1925, consequently the normalization begins with that year. The final factor is population change based on data from the U. S. Census for each of the 168 coastal counties that lie along the coast from Texas to Maine.

The generalized normalization method is determined as follows:

$NL_{present}$ = a storm's losses normalized to present values
y = year of storm's impact
c = county(ies) of storm's maximum intensity at landfall
L_y = storm's losses in year y, in current dollars (*i. e.*, not adjusted for inflation)
I_y = inflation factor, determined by the ratio of the present implicit price deflator for GDP to that of year y
W_y = wealth factor, determined by the ratio of the inflation adjusted present fixed reproducible tangible wealth expressed as per capita to that of year y
$P_{y,e}$ = population factor, determined by the ratio of the change in the population of the coastal county(ies) most affected by the storm from year y to present

The general formula for y = 1925 to the present is thus:

$$NL_{present} = L_y * I_y * W_y * P_{y,e}$$

For example, the 1938 New England hurricane made landfall as a Category 3 hurricane through the states of New York, Connecticut, Rhode Island, and Massachusetts causing an estimated $306 million damage. The population of the 11 coastal counties impacted at that time was 2.336 million, while the 1995 estimated population had increased to 4.860 million, a factor of 2.08. The inflation and wealth factors are 11.75 and 2.224, respectively, between 1938 and 1995. Thus, the normalized damage that would be attributed to the 1938 New England hurricane if it struck in 1995 is the following:

$306 million (1938) x 11.75 x 2.224 x 2.080 = $16,629 million (1995)

The normalized trend data on annual hurricane impacts from 1925-1995 is shown in Figure 85. It shows the estimated losses associated with each year's hurricane activity, as if each year's storms had made landfall in 1995. It presents a much different picture than the non-normalized data. It shows that in the 1940s, 1950s, and 1960s, more frequent and costly landfalls occurred than in the 1970s and 1980s, consistent with the climatology of hurricane landfalls. The normalized data also show that years with multi-billion dollar losses have been the norm rather than the exception.

In terms of the normalized data, in aggregate, hurricanes caused >$339 billion in losses over 71 years, or an annual average of about $4.8 billion, with a maximum of >$74 billion

To normalize past hurricane losses to a base year's values, it is assumed that losses are proportional to three factors: inflation, wealth and population.

in 1926 and numerous years with no reported damage. Of the 71 years, 35 years (about 50%) had less than $1 billion in damages. There were 19 years (about 25%) with at least $5 billion and 13 years (about 18%) with at least $10 billion. From this analysis, all else being equal, each year the U. S. has at least a 1 in 6 chance of experiencing losses related to hurricanes of at least $10 billion (in normalized 1995 dollars). Of course, in particular years, climate patterns can significantly alter these odds (Gray *et al.* 1997), and in every year beyond 1995 the stakes rise due to inexorable coastal population growth and development. The 1940s had 8 years with more than a billion in damages, as compared to the 1980s with only 3. Perhaps more importantly, it shows that the 1940s-1960s had 7 years of greater than $10 billion in damages, as compared with 1 in the 1970s and 1 in the 1980s. Through 1995, the 1990s have unfolded more like the 1940s than the 1980s. However, it does seem that the U. S. has been fortunate with respect to the more extreme losses from the standpoint of relatively few hurricanes making landfall during the recent period of greatest development. See Pielke and Landsea (1998) for more information.

In every year beyond 1995 the stakes rise due to inexorable coastal population growth and development.

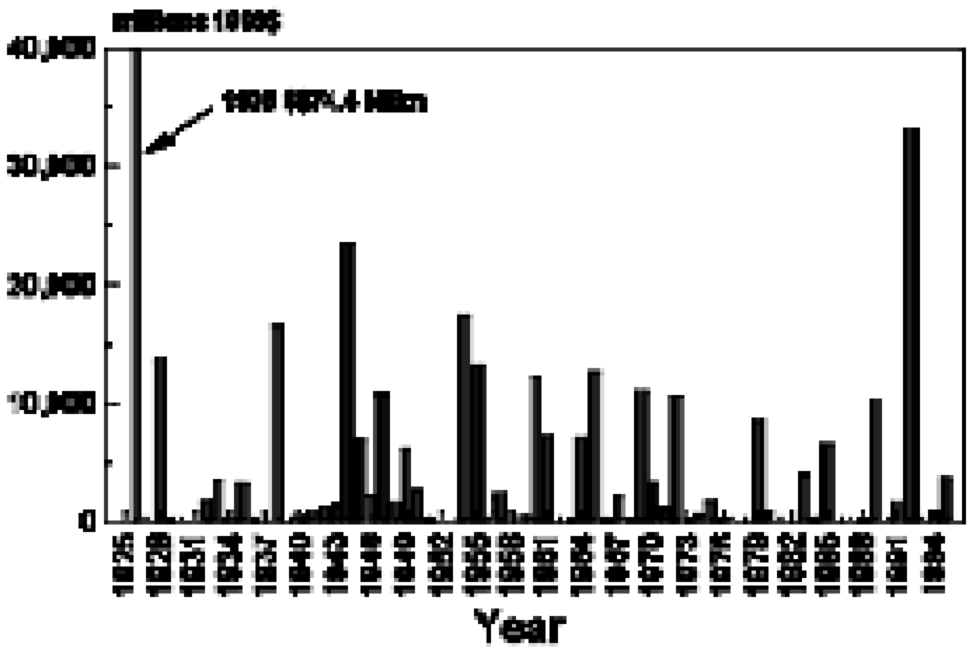

Figure 85
U. S. Normalized Hurricane Damage, 1925-1995
Time series of U. S. hurricane-related losses (direct damages in millions of 1995 U. S. Dollars) from 1925 to 1995 in normalized 1995 damage amounts (utilizing inflation, coastal county population changes and changes in wealth).

The intense hurricanes (Saffir-Simpson 3, 4 and 5) make up only about 21% of the U. S. landfalling tropical cyclones, yet account for about 83% of the normalized damage. The 52 intense hurricanes that struck the U. S. from 1925-1995 resulted in an average of $5.5 billion in damages per storm.

Conclusion

In conclusion, the selected research reported here suggests that it is possible to analyze data on societal impacts to discern related, underlying climatological and societal trends. In the case of hurricanes, the recent growth in losses is entirely attributed to growth in population and wealth. The normalized data suggest that recent decades have been less severe than those of the more distant past. In the case of damaging floods, a more complex picture emerges. First, it does seem clear that precipitation is related to damage at a national level, but of the ten measures examined, none explain more than 20% of the observed variance in damages. This leads to several tentative conclusions. First, it is necessary to move beyond total damages to per capita, or preferably, per floodplain-capita. Second, it would be useful to extend the analysis to a more regional basis, as different types of precipitation might be more closely related to damaging floods at smaller scales. Thus, the one clear picture that emerges is that changes in precipitation at a national level are not sufficient to explain changes in damaging floods. In this area, more research is required to develop more definitive conclusions. For a broader survey of the relationship of societal and climatological trends and impacts, see Kunkel *et al.* (1999).

It does seem clear that precipitation is related to flood damage at a national level, but of the ten measures examined, none explain more than 20% of the observed variance in damages.

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Climate Extremes and Adaptive Management on the Colorado River

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There has been, until recently, an almost total lack of regional capacity to implement plans relating to the impacts of climate variability and change.

There are four major issues within water management in the western United States which can produce critical conditions for planners, decision-makers and managers. They are extreme drought and floods; large-scale inter-basin transfers; quantification of tribal water rights, and; an energy crisis. These are sensitive to and exacerbate ongoing social dynamics of increasing population and consumption, deteriorating water quality, environmental water allocation, reserved water rights, ground-water overdraft, aging urban water infrastructures, the changing nature of Federal, State and local interaction, and variations in state laws. The result has been, until recently, an almost total lack of regional capacity to implement plans relating to the impacts of climate variability and change.

As these social trends evolve, extreme-event impacts research and applications are expected to assume greater immediacy with foci including impacts in urban areas, the public sector, scheduling, operations, and performance of various private sector activities, and assessment of users (Changnon, 1995). This paper focuses on the last three issues in particular relation to managing climatic risks in a multi-actor setting, the Colorado River Basin at Glen and Grand Canyons, during the El Niño-Southern Oscillation (ENSO) event of 1997-98. The study forms part of a more comprehensive project on decision-making and participation at the regional level in the Colorado River Basin in the face of climate variations and public goals (Pulwarty and Melis, 1999, in prep.).

The Colorado River system exhibits the characteristics of a "closing water system" (Kennedy, 1994) where, management of interdependence becomes a public function, development of mechanisms to get resource users to acknowledge interdependence and to engage in negotiations and binding agreements become necessary, and, implementation of such mechanisms does not appear to be viable without focusing events. Historical water allocation based on absolute quantities (made after the anomalously wet period of 1900-1925) raised significant concerns for geopolitical equity among the Basin States (and Mexico) through the 20th Century. This resulted in the Glen Canyon Dam being built about 20 miles above the Grand Canyon in 1963-64, effectively creating Lake Powell (Ingram et al 1990). The Colo-

rado River now dries up some 10-20 miles before reaching the Sea of Cortez (Gulf of California).

Management decisions in the Colorado River Basin cross many temporal and spatial scales (Table 16).

Table 16
Examples of cross-scale issues in Colorado River water management

Temporal scales	
Indeterminate	Flows necessary to protect endangered species
Long-term	Inter-basin allocations and those allocations among basin states
Decade	Upper Basin delivery obligations, life-cycle of humpback chub (*Gila cypha*)
Year	Lake Powell fill obligations to achieve equalization with Lake Mead storage
Seasonal	peak heating and cooling months
Daily-monthly	Flood control operations, Kanab ambersnail impacts
Hourly	Western Area Power Administration's power generation decisions
Spatial scales	
Global	Climate influences, Grand Canyon National Park World Heritage Site
National	Western water development: irrigation, Grand Canyon Protection Act (1992)
Regional	Prior appropriation, Upper Colorado River Commission, Upper and Lower Basin Agreements, energy grid
State	Different agreements on water marketing within and out-of-state, Water Districts
Municipal-community-household	

This paper describes the response of natural resource managers and operations on the Colorado River at Glen Canyon Dam to unanticipated spring runoff and flood-flow events.

This paper describes the response of natural resource managers and operations on the Colorado River at Glen Canyon Dam to unanticipated spring runoff and flood-flow events of 1983, 1984, and 1995, in the context of management objectives for maximum storage based on periods of drought (such as the 1930s, 1950s, 1977, and 1987-92). It shows the ways in which different lessons were used from these events to prepare for likely impacts related to the 1997-98 ENSO event. It also describes how new management approaches in the Colorado River Basin facilitated responses while still meeting seasonal and long-term ecosystem, cultural, inter-basin water resources and hydropower needs.

Adaptive Management

The aim of Adaptive Management (AM) is to increase the flexibility of a "managed" system to adapt to or recover from unforeseen consequences or "surprise" and for learning to recover from deliberate and passive ("natural") perturbations of the system. The most commonly employed method has been experimentation with flow regimes (such as the much-

publicized Spring 1996 releases) as a mechanism for maintaining ecological and cultural integrity of the system while still meeting economic requirements. The key principles of operation for AM to occur are (Lee 1993):

1) Cooperative management (shared decision-making authority)
2) Allowing for local variations in management strategies
3) Systematic learning using experimental designs

To facilitate achieving these requirements, the Adaptive Management Program (AMP) in the Glen/Grand Canyon region is composed of three equally balanced elements (1) a technical process, including the Glen Canyon Monitoring and Research Group (GCMRC), the Technical Working Group (TWG) and external peer review, (2) an administration coordination process that is headed by the Secretary's designee and (3) a decision process for making recommendations to the Secretary through his/her designee Adaptive Management Working Group (AMWG), approval by two-thirds consensus). The development of this program is considered elsewhere.

The two factors most often used for spring streamflow forecasts *prior* to the spring runoff period are snowpack conditions (including snow-water-equivalent, accumulated over the winter-season months) and antecedent conditions as indicators of soil moisture.

SESSION **2**

The data employed in this study include the results of 32 interviews, analyses of climate and streamflow data and model runs, historical and institutional analyses of water management in the basin, and participation and organization in several planning and decision-making meetings carried out by the GCMRC under the auspices of the AMWG. Interviews were carried out with TWG and AMWG representatives from:

1) Cooperating Federal and State agencies involved in preparing the *Operations of Glen Canyon Dam – Final EIS* (1995), that have management jurisdiction in the affected areas, including Bureau of Reclamation, Bureau of Indian Affairs, U. S. Fish and Wildlife Service, National Park Service, Western Area Power Administration, Arizona Department of Game and Fish, and the Upper Colorado River Basin Commission;
2) Six tribes: Hopi Tribe, Hualapai Tribe, Navajo (Dine) Nation, San Juan Paiute Tribe, Southern Paiute Consortium, Pueblo of Zuni;
3) The seven Colorado River Basin states: Arizona, California, Colorado, Nevada, New Mexico, Wyoming, and Utah;
4) Environmental groups, recreation interests, and contractors who purchase Federal power from Glen Canyon Dam through the Department of Energy, including American Rivers, Grand Canyon Trust, Grand Canyon River Guides Association, Trout Unlimited, and the Colorado River Energy Distribution Association.

Personnel with responsibilities for streamflow forecasts at the National Weather Service's River Forecast Center and operations of Glen Canyon Dam at the Bureau of Reclamation (BOR) were also included in the interview process. Streamflow data for 27 points (1905-1990) in the CRB, (and 1898-1998 at Lee Ferry) were obtained from BOR and climate data for the entire region were obtained from NOAA.

The Climate Forecast Issue

Traditionally, the ideal operating plan of Glen Canyon Dam from a hydropower perspective would enable Lake Powell to fill each year and meet downstream requirements, without risking flood flows. The two factors most often used for spring streamflow forecasts *prior* to the spring runoff period are: (1) snowpack conditions, including snow-water-equivalent,

accumulated over the winter-season months (December through March), and (2) antecedent conditions as indicators of soil moisture (water retention capacity). The climate-related parameters that govern forecasts issued monthly and updated every two weeks *during* the main Spring runoff period (April through July) are: (1) the variability and extreme precipitation from the end of the accumulation season (e. g., 1 April); (2) temperature extremes and, (3) the historical timing of Spring snowmelt and its magnitude and duration including snowpack-runoff relationships.

With respect to operations of Glen Canyon Dam, the lowest point of storage in Lake Powell during the water year usually occurs in March as a result of January-March releases being greater than inflow. It is thus the storage by the end of March that actually prepares the reservoir for the spring runoff period. More recently, the Biological Opinion (DOI, 1994) for the Colorado River below Glen Canyon Dam, requires that conditions suitable for endangered and other native fish species be provided by evaluating hydrologic patterns similar to the pre-dam hydrograph.

Hydrologic Triggers

During water year 1998, hydrologic triggering criteria for spring Beach/Habitat-Building Flows (BHBF) were developed by the TWG as follows: High flows would be released:

1) If the January forecast for the April-July unregulated spring runoff into Lake Powell exceeds 13 million acre feet (MAF) (about 140 percent of normal) when the January 1 storage is 21.5 MAF (i. e., when the sum of forecasted runoff and reservoir storage exceeds 34.5 MAF on January 1), or
2) If any later monthly forecast for spring runoff into Lake Powell would require a powerplant monthly release greater than 1.5 MAF.

Either of these triggers implicitly recognizes that there is a significant risk of a flood flow during the peak of spring runoff. Flood flows occur when power plant capacity is exceeded. Spill risk is thus higher if the reservoir is filled during the preceding year.

A major "focusing event" in the basin was clearly the 1983 flooding that occurred throughout the Colorado River Basin.

To Every Season there are Extremes:
The Problem of Extreme Event Management

A major "focusing event" in the basin was clearly the 1983 flooding that occurred throughout the Colorado River Basin. The years of reservoir filling from 1964-1980 left Lake Powell and the entire Colorado River storage system full just prior to the extremely high runoffs in late Spring through early Summer 1983. Variability was thus removed from the flow system as Lake Powell and other reservoirs were filled. This period of filling of the largest capacity reservoirs allowed for continued development and human encroachment into the flood plains of the river in the Lower Basin (Rhodes et al. 1984) with almost no risk from flood flows. The "memory" of widespread uncontrolled flooding in 1983-84, with potential for dam-failure at Glen Canyon in 1983 (Director, Upper Colorado River Basin Commission, pers. comm.) still causes concern among managers in the region, even among those who were not in management positions at that time. Whether or not extreme total runoff in 1983 was owed solely to the 1982-83 ENSO event is still unclear. The most important factor in addition to extreme late-spring precipitation was the anomalous cold weather that persisted through July and kept snowpacks on the higher elevations into early summer.

Information in Table 17 illustrates that simply forecasting or showing a trend in extreme event occurrence is not enough to lead to useful adjustment actions that managers are able to implement. The forecast problems for 1983 and 1984 (24.0 and 24.5 MAF, respectively — the two wettest years on record) were completely different with respect to runoff timing, although both events occurred under full reservoir storage conditions. As a result, these extreme events were anticipated and responded to very differently by dam operators and other related managers. For example, by early winter (January), based on accumulated snowpack, it was clear that 1984 was going to be a high runoff year, and the forecast turned out to be quite accurate. In contrast, each of the 1983 monthly forecasts during the first four months of that year indicated that average or below normal April through July runoff would occur. In late spring 1983 runoff began to increase from 117% in May to 210% in June. Although a similar runoff and runoff scenario occurred in spring 1995 (20.5 MAF), when the error for the January forecast was 5 MAF (in a 14 MAF system), similar consequences related to prolonged flood flows were avoided only because Lake Powell had been drawn down, a result of several low runoff years between 1987 and 1995. However, the late inflow scenario of 1995 was the extreme event that allowed for Lake Powell to approach storage capacity again after nearly a decade. The lack of public awareness about the late, high-magnitude runoff in 1995, likely owed to the fact that the risk of flood releases was zero because of large reservoir storage capacity due to previous drought.

Each of the 1983 monthly forecasts during the first four months of that year indicated that average or below normal April through July runoff would occur. In late spring 1983 runoff began to increase from 117% in May to 210% in June.

Total storage within Lake Powell is over three times the annual Upper Basin allotment, or about 25 MAF. However, large forecast errors associated with snowmelt-runoff transformations during periods when antecedent storage conditions are near capacity mean that a forecast of winter precipitation alone is inadequate to meet user needs, especially for flood control, and other resource management issues associated with the AMP.

Table 17
Flows since closure of Glen Canyon Dam near or above Power Plant Capacity 31,500 cubic feet per second (cfs) that have (bold) or might have produced flood flows (JFM = Jan-Feb-Mar, AMJ = Apr-May-Jun)

			April-July Runoff million acre feet			700 mb Temp. ˚C anomaly	
		cfs	Forecast				
Year	Peak Flow	000s	Jan 1	Apr 1	Observed	JFM	AMJ
1965	May-June	65	9.6	11.4	11.3	-1.5	0.5
1973	June	33	10.1	9.0	11.3	-1.0	-2.0
1983	**June-July**	**96.2**	**7.8**	**7.9**	**14.8**	**0.8**	**-2.0**
1984	**June**	**50**	**13.0**	**11.5**	**15.4**	**-1.8**	**-1.5**
1985	May	55	11.5	10.3	11.7	-1.8	0.5
1986	June	48	10.6	10.8	12.6	1.5	0.5
1995	**May-June**	**66**	**6.0**	**8.3**	**11.7**	**1.5**	**-2.0**
1996	March-April	45	6.3	8.9	7.3	1.0	1.0
1997	Feb-July	27	12.0	12.0	11.4	1.5	-0.5
1998	**May-July**	**25**	**6.6**	**6.8**	**7.7**	**0.8**	**-0.8**

Operations in Water Year 1998

Water year 1998 experienced near-normal hydrologic conditions in the basin with near normal precipitation translating into average snowpack (AOP, 1998, 1999). At the beginning of the runoff season the basin-wide snowpack was 100% of normal but soil-moisture conditions and winter runoff were above normal owing to wetter than normal conditions throughout 1997. Great media and public attention focused on the strong ENSO anomaly present in the equatorial region of the Pacific Ocean and the potential effect this might have on the Colorado River Basin, particularly the Upper Basin, with respect to spring runoff magnitude. Few Colorado River managers or forecasters focused attention on potential for dramatic seasonal shifts in snowpack accumulation, delayed runoff or likelihood for high-elevation temperature anomalies, all lessons that should have been learned from the 1982-83 ENSO (the only other event of comparable magnitude within recent experience). However, additional reservoir draw-down of Lake Powell was an exceptional move by BOR, in that operators heeded historical data on both precipitation and temperature, particularly with respect to 1983 and 1995, rather than operate solely on the basis of the early, below-average runoff forecasts. During the winter of 1998, scheduled releases from Glen Canyon Dam remained above those suggested by the forecast from January through March. This resulted in an additional drawdown of about 1 MAF above the storage that would have otherwise been available at the end of the spring runoff season. This action constituted a unique and conservative management strategy intended to prepare for potential high and late spring runoff on the basis of prior experience (learning). While water year 1998 did not have the extremely high spring precipitation, and the large warm winter-cold spring differences that characterized water year 1983, it posed a forecast and management problem in a different way. The decision to make high releases had to be made by late-December 1997, a time when most forecasts are likely to assume normal conditions based on historical mean data.

Extremes result in disasters when they exceed organizational capacity to respond.

All Extremes Will Not Remain Equal

Extremes result in disasters when they exceed organizational capacity to respond. After the end of the 1998 water year, it was clear that if releases, at constant powerplant flows above 25,000 cfs, were not made from Glen Canyon Dam (GCD) during January-March, a spill event (either exceeding power-plant capacity or of 0.5 MAF) would have likely occurred at the beginning of summer (R. Peterson, BOR Operations, pers. comm.). In addition, if an event similar to the 1983 flood had occurred, damages would have been minimal by comparison. This is a case of having the anticipated event (extremely high runoff) not being as large as expected, but of managers still having to make hedges and adjustments beforehand in accordance with the diverse needs within the river system. Factors that actually led to and facilitated actions are summarized in Table 18. River managers faced considerable pressure from both power and environmental groups not to allow higher than normal (forecasted) flow releases during winter and early spring 1998. Environmental groups felt that if releases continued, then the triggering criteria would not be met (misunderstanding of the hydrologic triggering criteria by some stakeholders). Meanwhile, hydropower interests were concerned about the likelihood of a drier than normal summer that would restrict diurnal powerplant operations. Discussion of other AMP objectives and an analysis of the role of the AM process is provided in Pulwarty and Melis (1999).

The relatively dry period of 1987-1992 and in 1994 had reduced somewhat the sense of urgency immediately after the 1983 floods. However, the initial under-forecasting of the high runoff year 1995 (20.8 MAF) raised concern not among the public, but mainly among the GCD reservoir managers who are obligated to use forecasts to schedule monthly and annual operations.

The spring 1995 scenario and continued higher than normal runoff for 14 consecutive months in 1996 through 1997, helped set the stage for mutual cooperation between the climate research community (at the NOAA Climate Diagnostics and Climate Predictions Centers) and water managers (BOR) on the Colorado River.

Conclusions

In many case-studies of extreme event impacts it is still difficult to determine how or whether present management approaches have used lessons accumulated over previous events. Even after the events of 1983, the Phase II, GCD Final EIS (DOI, 1995) (which has become the baseline for AM modeling efforts in the Colorado River Basin) was carried out during virtually the same period as the 1991-1995 ENSO event. Although an extremely persistent ENSO event was documented during the 1991-1995 period, no AMP representative recalled explicit consideration of the long-term event as creating an anomalous background against which baseline studies were being carried out when interviewed. It should be noted however that the GCMRC is now considering the explicit use of climate information within their AMP conceptual simulation model development.

In many case-studies of extreme event impacts it is still difficult to determine how or whether present management approaches have used lessons accumulated over previous events.

As is evident from this study, moving beyond the commonly held assumptions of climate information use as a one-way or even two-way linear communication from researchers to practitioners and policymakers, the latter somewhat pejoratively referred to under the umbrella of “users,” requires a mix of problem solving *and* interactionist approaches (see Table 18). This illustrates the necessity of understanding the context of use, an appreciation of the ways in which information becomes acceptable for use, and the need for reframing questions from the points of view of those affected, rather than by simply specifying the physical risk.

Table 18

Factors in the decision to prepare for the 1997-98 ENSO event and to use climate information in Spring 1998 at GCD

1) Previous Events:
   - 1983 as a focusing event for public and private concerns: Association of high, late runoff with 1982-83 ENSO and forecasts of lower than normal runoff
   - 1984 magnitude, timing and forecast of high runoff
   - 1995 as a focusing event for GCD managers: 5 MAF forecast error for late-spring,
   - 1997 antecedent high runoff conditions 140% inflow to Lake Powell,

2) Consequences of flood events seen (by managers) as more direct than single year drought: Reservoir capacity has 2-4 year buffer for dry periods,

3) ENSO 1997-1998
   - regional/national pressures to "do something about El Niño,"
   - concern about an exceptional event or a "surprise,"

4) Trust in Reservoir Manager by Upper Basin interests: States River Commission, and Power marketers,

5) Acceptability of climate information. Enabled by:
   - increased credibility of climate information providers by interaction throughout the water year and explicitly addressing concerns/doubt
   - willingness of climate researchers to develop an appreciation of the context and procedures of decisions within the basin (e. g. role of RFC vis-a-vis BOR, power, flood control, environmental needs etc.),
   - explicitly addressing known barriers to information use obtained from previous studies (Pulwarty and Redmond, 1997),
   - communicating key components of climate variability in region through data presentation to stakeholders, and exercises in climate data analysis with reservoir operations personnel,
   - identifying thresholds (that matter) passed in year to date (also other regions),
   - judgment and experience of reservoir operator in using predictions, e. g., realizing that more information may not help, and making decisions under uncertainty,

6) Flexibility and process for interaction allowed through the Adaptive Management Process.

While there is now the needed focus on trends in extreme event occurrence and decadal scale variations, there is still limited knowledge of how the evolution of responses between events shapes the use of information and preparedness. Indeed, while there are increasing numbers of studies on the potential losses of past events in the context of present day property exposure, such estimates of losses, of necessity, present a dynamic view of exposure but a static view of the evolution of responses and other forms of vulnerability. Neither loss estimates nor mitigation or adjustment should be assumed to be the same over time.

Precision of a forecast or prediction may be less important than making sure that major factors are not left out of the analysis (see Table 19). As in this case, the new requirements to balance economic interests, environmental management objectives on the Colorado and the need to find mutually reinforcing ways of doing so, are directly the result of changing social values and views about environment-society interactions. These factors can only be distilled from comparative appraisals of current and past practices, evaluation of the decision processes employed, and by carrying out experiments in information use. An assessment of forecast "value" should be evident in a change in decision strategy (both cautious or opportunistic) and in raising the level of task performance.

Precision of a forecast or prediction may be less important than making sure that major factors are not left out of the analysis.

Table 19

Some factors identified as affecting the degree of climate information utilization (see also Pulwarty and Redmond, 1997; Changnon et al., 1996, Glantz, 1994).

- The nature of information and its development
- Identification of competitive users
- Identification of actual and potential users and awareness of information available
- Role of the user in determining the relevance of information produced and the development of products: what is provided and what is actually being asked for?
- The communication process and the communicator experience
- The characteristics of the user and the acceptability of information
- The nature of decisions and context of use
- Clear identification of benefits
- Evaluation of consequences of use and alternatives
- Measures of refinement and interaction over time, i. e. learning and innovation among user, provider and intermediary

While there is now the needed focus on trends in extreme event occurrence and decadal scale variations, there is still limited knowledge of how the evolution of responses between events shapes the use of information and preparedness.

Roger Pulwarty makes a point during an informal discussion.

Is There a Discernible Influence of Climate Change On Wildlife?

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The distribution and abundance patterns of wildlife are not only of intrinsic interest to biologists, but are part of folklore and cultural values in most, if not all, societies. Because climate has long been known to be a powerful force helping shape wildlife patterns, any changes in climate would naturally be expected to be reflected in alterations to the abundance and range limits of many species. Moreover, because many species of wildlife depend on vegetation for food, shelter and nesting sites, climatic impacts on vegetation can have secondary impacts on wildlife via alterations to vegetation patterns. Vegetation and animals might respond at different rates to a given climatic change event, thereby implying that communities of species could be disaggregated. This possible "tearing apart" of communities may in turn affect the "services" ecosystems provide to humans (*e. g.*, spruce budworm predation by birds). Although economic arguments based on the cost of the disruption of such services do contribute somewhat to the concerns that have been expressed about disruptions to natural communities by climatic changes, the high value placed by most cultures on wildlife preservation for aesthetic, ethical, recreational, and hunting criteria, as well as many other services not yet taken into account, requires us to vigorously investigate possible impacts.

Vegetation and animals might respond at different rates to a given climatic change event, thereby implying that communities of species could be disaggregated.

I have undertaken an investigation of possible impacts of climatic trends on wildlife using an informal data set (collected by a professional naturalist) of 30 years of arrival times of birds migrating in the Spring to Germfask, which is in the Upper Peninsula of Michigan. Some of these migrating birds over-winter in the tropics, while others stay only a few hundred kilometers south of Germfask, which means that time of arrival is different for these various birds, because their travel-time is quite different. Not only did the data set allow me to look for the variability due to time, but I could also look for possible changes in arrival times over the years, searching for any possible systematic patterns.

The data set was first checked for obvious biases due to possible recording gaps. No such significant problems were found. Both passerines (songbirds, there were 31 such species) and non-passerine (*e. g.*, ducks, cranes, grouse) species were recorded, making a total of 47 species with Spring arrival dates recorded frequently enough over the 30-year period to comfortably consider the data as reliable. Four patterns were observed to have occurred between 1965 and 1994:

- **extension of ranges northward:** *i. e.*, bird ranges expanded and such migrant species (*e. g.*, Mourning Dove) became permanent residents (8.5%)
- **earlier arrivals:** *i. e.*, the date of the first spring arrival occurred at least 7 days earlier

in 1994 than it did in 1965 (32%)

- **no significant change in arrival dates:** *i. e.*, the first arrival times did not change more than 6 days earlier or later over the 30 year period (57.5%)
- **later arrivals:** *i. e.*, first individual seen of a migrating bird arriving at least 7 days later over the same period of time (2%)

One possible climatic indicator, which integrates many of the ecologically most important aspects of climate (*e. g.*, temperature, solar radiation, snow fall), is the thawing of ponds and lakes. The "ice-off" dates for the lake in Germfask over the same 30-year period show a trend towards earlier thawing. Indeed, there was a significant correlation between these ice-off dates and the dates of those migrants arriving earlier. Thus, these associations are at least suggestive of a climatic cause of the highly significant difference between the percentages of earlier (32%) and later (2%) arriving species.

Birds in all three categories arrived on average around 18 to 20 days earlier in 1994 than in 1965.

But if this correlation is indicative of a climatic cause, how could species in Central America know what the climatic conditions in Michigan were? To study this topic, I divided the earlier-arriving species into short- (northern boundary of wintering range below 35° N latitude), medium- (below 30° N latitude) and long- (below 25° N latitude) distance migrants. Birds in all three categories arrived on average around 18 to 20 days earlier in 1994 than in 1965. Notably, birds wintering closer, in say Kentucky, where climatic anomalies in Michigan might be correlated with its anomalies, arrived nearly three week earlier, while birds flying from south of the U. S. border also arrived around three weeks earlier. The mechanism for this similarity in earlier arrival trends from migrants wintering in such different locations cannot be uniquely determined from only one observing point in Michigan. Thus, future research plans are to examine bird netting data from all over the country to see if waves of migration can be detected and dated.

But one may speculate in the following manner based on these results, even at this stage. Suppose a warming trend resulted in earlier greening of vegetation and melting of ponds, which were detected by individual short-distance migrants "eager" to arrive on the breeding ground before all of the best territories are filled by other individuals. This could possibly create a large wave of earlier arriving birds that would increase the probability of a detection of first arrival in Germfask. Individuals of the same species that winter farther south (usually females and younger birds) follow the lead of the earlier birds (usually males) but several days later. Meanwhile, as birds migrating from longer distances begin interacting with fewer short-distance migrants on their wintering grounds, they begin to also leave their wintering areas earlier. In essence, this "domino theory of migration" could explain how migrants thousands of kilometers away from their breeding ground would "get the word" that conditions in Michigan permit earlier migration. In essence, such a message is telegraphed by the earlier departures of short-distance migrants to medium-distance migrants and in turn to longer-distance migrants. This speculation is bolstered by the fact that the absolute arrival dates (not trends in arrivals) of short distance migrants are typically a few weeks earlier (in 1994 around April 1) than medium- and long-distance migrants (in 1994 around April 30).

In short, while much work yet remains to be done to confirm these significant results from only a pilot study, they certainly do suggest that there is a discernible influence of climate change on wildlife.

A second example of both the impacts of climate on wildlife and the potential for associated loss of ecosystem services is the warbler/spruce budworm interaction.

Price (personal communication) has mapped the breeding ranges of most North American bird species, and correlated these to a number of climatic predictors. Very significant fits were obtained by this correlative procedure for most species. Price then projected future range distributions for a doubled carbon dioxide world based on the climate change projected by the Canadian Climate Center climate model. He projects a significant decline in warbler species richness in heavily forested areas of Canada currently vulnerable to spruce budworm attacks. Because warblers can control more than 80% of the budworm larval population in non-outbreak years, a loss of warbler populations or the passage during migration of budworm-eating species at the wrong time relative to budworm development stages could trigger a change in the likelihood of major outbreaks of this number one forest pest in Canada. Price's calculations raise the obvious possibility of such cascading effects through economically and aesthetically important ecosystems as a result of typically projected climatic changes.

These results do clearly indicate a plausible chain of events from human activities that modify atmospheric conditions to responses by some birds, which affect specific insects, which influence forest health, which could affect humans aesthetically and monetarily.

Of course, several caveats are in order. First, the technique used to project future range distributions from climatic changes is correlative, not a physiologically-based mechanistic explanation (see Root and Schneider, 1995 for a discussion of various modeling approaches and their advantages and disadvantages). This means that additional studies to test the reliability of the projections for each species are needed before a high level of confidence should be assigned to the projected outcomes. Second, birds are not the only factor influencing budworm outbreaks, nor is climate the only factor controlling bird migration times or population sizes. Nevertheless, these results do clearly indicate a plausible chain of events stretching from human activities that modify atmospheric conditions to responses by some birds, which in turn affect specific insects, which in turn influence forest health, which in turn could affect humans aesthetically and monetarily, by increasing costs both of pesticides (which have their own cascading events) and timber.

A third example of the kinds of impacts climate change could have on wildlife arises in the Prairie Pothole Region of the Great Plains. This region is known by duck enthusiasts and hunters as the prime North American breeding grounds — 50% of waterfowl breed in this region, mostly in ephemeral spring ponds. The U. S. Fish and Wildlife Service has found that yearly fluctuations in duck populations correspond closely with yearly number of so-called May ponds. If climate change were to create, as typically projected, increasing temperatures in this part of the world, then only if there were a substantial increase in precipitation could the extra evaporation associated with a warmer climate prevent a drying trend for the May ponds — and likely reduction in duck populations.

Sorenson et al. (1998) investigated this possibility by correlating the duck population data with a direct measure of climate: the Palmer Drought Severity Index (PDSI). This correlation was even more striking than that between duck populations and May Pond counts. They then calculated the PDSI for scenarios of climatic change embracing values typically projected for the mid 21st century: warming of several degrees and precipitation increases or decreases of ten to fifteen percent. These sensitivity analyses showed that only very low temperature increase and high precipitation increase scenarios prevent a loss of duck populations, but for more than a few degrees warming and no precipitation increase the current duck populations (estimated at about 5 million breeding pairs on average) could be drastically reduced. If precipitation were to decrease as well, even by only a few percent, then the average duck population could decrease to less than half the present average. Although some ducks might breed farther north, as they have in the past in dry years in the Pothole region, nesting success is lower.

Therefore, like the spruce budworm/warbler decline hypothesis, the waterfowl loss/drying association requires further study, but already commands attention to the plausibility of significant impacts of climate change on wildlife. The studies of bird-arrival dates in Michigan, which show arrivals weeks earlier over the past thirty years, are paralleled by studies of egg laying dates in England (Crick et al., 1997), upslope bird migrations in Costa Rica (Pounds et al., 1999, Still et al., 1999) and butterfly range limit changes in California and Europe (Parmesan, 1999) discussed by Parmesan in this AGCI volume. Taken together, these early pieces of evidence do not prove, but certainly strongly suggest, that there may already be a discernible influence of climate change on wildlife.

Like the spruce budworm/warbler decline hypothesis, the waterfowl loss/drying association requires further study, but already commands attention to the plausibility of significant impacts of climate change on wildlife.

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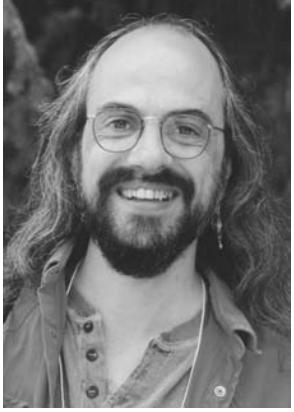
Terry Root discusses the influence of climate change on wildlife.

These early pieces of evidence do not prove, but certainly strongly suggest, that there may already be a discernible influence of climate change on wildlife.



Climate Change Signal in the Annual Cycle of Temperature, Diurnal Temperature Range and Precipitation

Results from Several ECHAM4/OPYC3 Climate Change Experiments

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In terms of its impact on society and ecological systems, a possible climate change due to human activities is more adequately described by extremes rather than mean values.

S E S S I O N **2**

In terms of its impact on society and ecological systems, a possible climate change due to human activities is more adequately described by extremes rather than (global) mean values of, for instance, surface temperature. Indices which describe extreme events in the climate system are *e. g.*, the contrast between the seasons, diurnal temperature range, and frequency and strength of rainfall events. In this presentation, the climate change signals as simulated by a set of experiments using a General Circulation Model (GCM) were therefore considered for the annual cycle of near surface temperature, diurnal temperature range (DTR) of near surface temperature and precipitation statistics. First, a regional comparison for these parameters was presented, then the GCM-derived patterns of climate change were used for (optimal) detection of externally forced climate change.

The GCM experiments were performed at the Max-Planck-Institute of Meteorology, Hamburg using their newest T42 model version, ECHAM4/OPYC3, with a horizontal resolution of approximately 2.5° x 2.5° (Röckner *et al.*, 1998). The 19-layer ECHAM4 atmospheric model (Röckner *et al.*, 1996) was coupled to the OPYC3 ocean model with 11 internal isopycnal layers using flux adjustment for the annual means of heat and freshwater. Besides a 300-year control simulation of the present-day climate (CTRL) three climate change experiments starting in 1860 have been considered using observed concentrations of well-mixed greenhouse gases and sulfate aerosols until 1990 and changes according to IPCC scenario IS92a (IPCC, 1992) thereafter: GHG (until 2100) was forced with changes in greenhouse gases only, GSD (until 2050) incorporated the direct (radiative) effect of sulfate aerosols in addition to changes in greenhouse gases, and GSDIO (until 2050) used the forcing of GSD plus changes in tropospheric ozone and the indirect effect of sulfate aerosols on cloud albedo (see Röckner *et al.*, 1998 and Bengtsson *et al.*, 1998 for a more detailed description of forcing scenarios).

Regional Climate Change

Six regions have been selected to present comparisons between the annual cycle of observed and simulated parameters (averaged over the respective region): Central/Northern Europe and five regions proposed by IPCC, 1990, Central North America, Southern Asia,

Sahel, Southern Europe and Australia (see Cubasch *et al.*, 1995 for definition of regions). For near surface temperature the annual cycle of monthly means simulated by ECHAM4/ OPYC3 (CTRL, and GHG, GSD, GSDIO for 1950-79) agrees fairly well with an observed monthly climatology for 1950-79, except for a slight underestimation of model temperatures over Southern Asia and the Sahel.

For monthly precipitation totals the phase of the annual cycle is simulated fairly well except over Central/North Europe whereas the largest observed versus modeled differences in the amplitude occur for Central/North America, Southern Asia and Central/North Europe. For DTR and precipitation intensities a comparison to observations was not possible since no observed climatologies were available at the time of the presentation.

All three climate change experiments simulate increasing temperatures over the six regions throughout the year for the period 2020-2049. The largest change in the annual cycle occurs over Central/North Europe with an increase of 4.5˚K in winter and 2˚K in summer for GHG. Temperatures over Central North America increase by about 4˚K in summer and 3.5˚K in winter. These changes are smaller for the sulfate aerosol experiments GSD and GSDIO. DTR decreases in GHG over all regions throughout the year, except for an increase over Central North America by about 0.4˚K in summer and an increase over Europe by about 0.1˚K in late summer. Again, these changes are smaller in the sulfate aerosol experiments. The most prominent changes for monthly precipitation are increases over Southern Asia and the Sahel throughout the year in all three experiments (up to 1 mm/day over Southern Asia in summer), an increase over Central/North Europe in winter and a decrease over Australia in winter.

For Central/North Europe the GHG model simulates an increase of 4.5˚K in winter and 2˚K in summer. Temperatures over Central North America increase by about 4˚K in summer and 3.5˚K in winter.

In terms of precipitation-related parameters events of heavy rainfall are more important for climate change impacts than mean monthly precipitation. Figure 86 shows a comparison of the share of eight intensity classes on the total monthly precipitation between the periods 1960-1991 and 2020-2049 in GHG for four of the six regions. Over Australia the share of all intensity classes stays relatively stable. Over Central North America the share of heavy rainfalls increases throughout the year, especially in summer. In Southern Asia and the Sahel the increase of precipitation totals in all months is caused by increases in heavy rainfall. Over Europe (not shown) the relative share of heavy rainfall also increases.

Climate Change Detection

Optimal fingerprint methods have been used for the detection and attribution of anthropogenically caused climate change in observational records of near surface temperature (*e. g.*, Hegerl *et al.*, 1996). Only more recently, other geophysical parameters are included in detection studies. Also, these techniques have been mostly applied to decadal, annual or seasonal averages. As an extension of these studies, the optimal fingerprint method as proposed by Hasselmann (1993) was therefore applied to annual means and the annual cycle of temperature, DTR and precipitation. The optimal fingerprint method consists of rotating a spatial pattern of expected climate change (guess pattern) in directions of low climate noise to maximize the signal-to-noise ratio. The projection of observed (moving window) trend patterns onto this optimized fingerprint pattern (detection variable) is then tested against natural climate variability to infer unusual changes (*i. e.*, changes greater

than to be expected from natural variability within a certain confidence limit) in the recent record (see Hegerl *et al.*, 1996 for details). The extension of this approach to a multi-fingerprint analysis which can be used for the attribution of climate change to different causes (see *e. g.*, Hegerl *et al.*, 1997) is not discussed here.

For the simulated precipitation, the relative share of heavy rainfalls on the monthly totals increases in a changed climate due to increased greenhouse gas concentrations, especially over Central North America in summer and over Southern Asia and the Sahel.

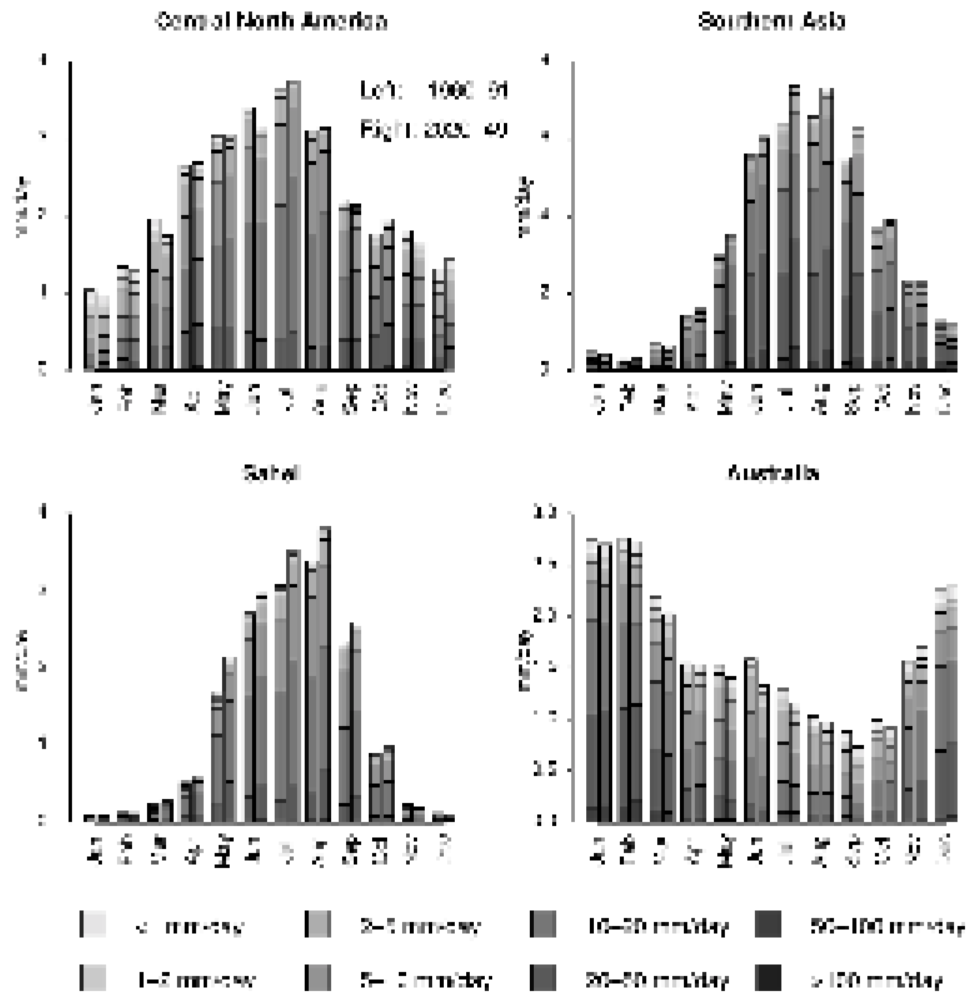

Figure 86
Share of eight intensity classes (legend on right, in mm/day) on the total monthly precipitation (y-axis in mm/day) between the periods 1960-91 (left bars) and 2020-49 (right bars) in experiment GHG (greenhouse gases only) for four of the six regions.

In the presentation only the non-optimized version of this approach was discussed where the fingerprint pattern is set equal to the guess pattern. In this summary, though, the optimized analysis is also presented. Also, instead of representing the annual cycle as the cosine and sine coefficients of the first harmonic, an amplitude/phase representation is used here focusing on the amplitude of the annual cycle only. The annual cycle was derived from the

respective data fields by complex demodulation followed by the application of a low-pass filter. Only the amplitude of the temperature annual cycle is discussed in this section for brevity deferring the other parameters to the conclusions.

Figure 87 shows a first guess of the expected climate change for the amplitude of the annual temperature cycle as given by the dominant Empirical Orthogonal Function (EOF) of the GHG experiment (anomalies relative to the 1961-1990 mean). Throughout the analysis all fields are subjected to an observational mask indicating where sufficient observations are available in the last five decades. As indicated by the corresponding Principal Components (not shown) the first EOF carries most of the climate change signal whereas all other EOFs represent climate noise. The prominent features of the guess pattern are a decrease of the amplitude over most of the continents except for an increase over the Western U. S., Southern Europe, Southern South America and parts of Australia. Note that the amplitude of this guess pattern is not important for the optimal fingerprint analysis so that the EOF can be interpreted as a trend pattern of expected change derived from the first 1000 years of a control simulation performed with the Hamburg ECHAM3/LSG model (starting in year 301). The difference between the guess pattern and the resulting optimal fingerprint (not shown) is mainly an attenuation of the amplitude decrease over the northern high latitudes and an amplification of the amplitude increase over Southern Europe. To reduce the number of degrees of freedom and thereby allowing for a reliable estimation of the covariance matrix, all time series of 31-year trends were projected onto the first 10 EOFs of the GSDIO simulation prior to the analysis.

An optimal fingerprint algorithm is applied for climate change detection in the annual means and the annual cycle of near surface temperature, diurnal temperature range and precipitation.

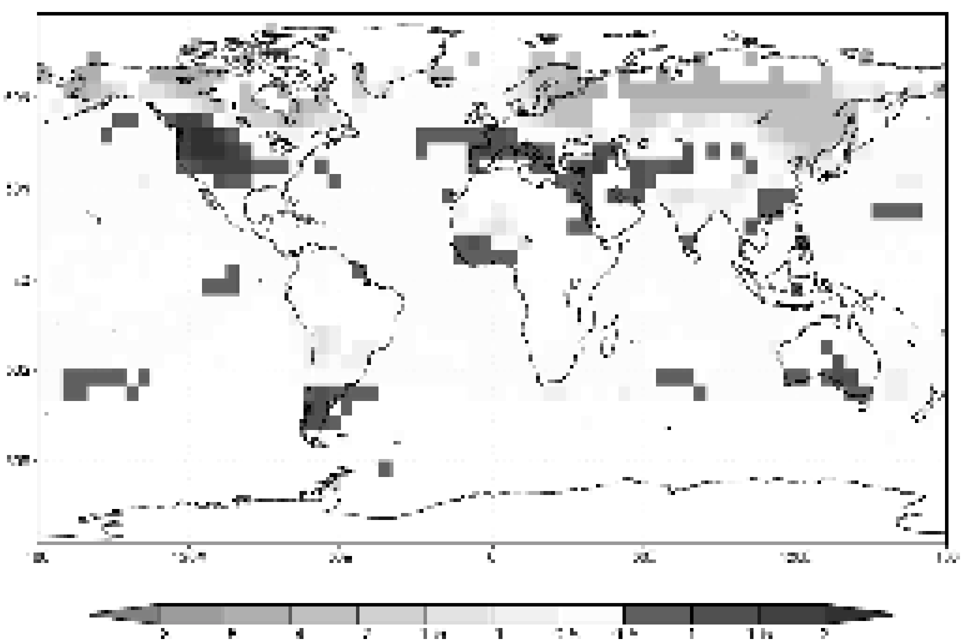

Figure 87
Dominant Empirical Orthogonal Function of the amplitude of the annual cycle of near surface temperature in GHG (guess pattern).

Figure 88 shows the detection variable derived by projecting the time series of 31-year (moving window) trend patterns of the amplitude of the annual cycle of observed near surface temperature (Jones and Parker observed temperature data set; Parker *et al.*, 1994) onto the optimal fingerprint pattern, namely the last 700 years of the ECHAM3/LSG control experiment and the ECHAM4/OPYC3 control simulation. It can be seen that the observed detection variable leaves the 95% confidence band for the most recent observational record indicating that the trends were larger than is to be expected from internal natural causes alone. The most recent trends are thus not inconsistent with the hypothesis that they are caused by external factors (anthropogenic or natural external forcings). Also indicated in Figure 88 are the detection variables computed for the GHG, GSD and GSDIO experiments. They more or less agree with the observed trends indicating that greenhouse gas and/or sulfate aerosol forcings might be possible explanations for the unusual increase. However, to distinguish between the different causes a multi-fingerprint approach has to be applied.

The observed detection variable leaves the 95% confidence band for the most recent observational record indicating that the trends were larger than is to be expected from internal natural causes alone.

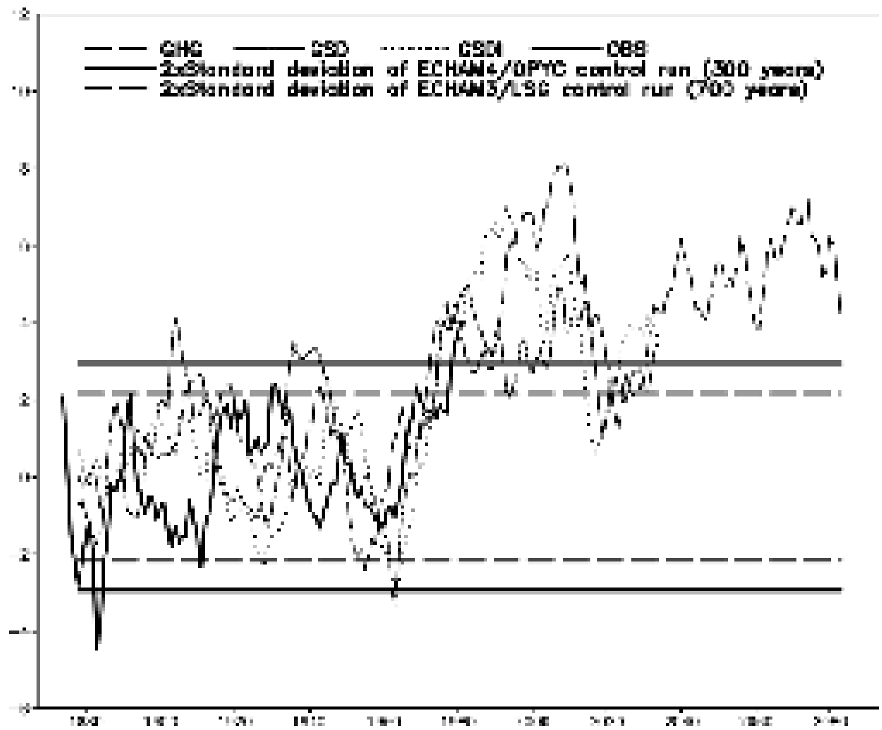

Figure 88
Detection variable for 31-yr trends of the observed amplitude of the annual temperature cycle (solid).
The horizontal lines represent twice the standard deviations of the same detection variable derived from the second 1000 years of the ECHAM3/LSG and from the ECHAM4/OPYC3 control experiments, respectively. Also shown are the detection variables derived from 31-yr trend patterns of the GHG (long-dashed), GSD (short-dashed) and GSDIO (dotted) climate change experiments. The time axis corresponds to the middle of the 31-yr trend windows. The unit on the y-axis is arbitrary. Note that the detection variables correspond to 31-yr trends, periods of constant detection variables therefore still indicate increasing amplitudes.

Conclusions

The climate change signals as simulated by several climate change experiments performed with the newest Hamburg ECHAM4/OPYC3 climate model have been evaluated for a few parameters related to climate extremes: annual means and the annual cycle of near surface temperature, diurnal temperature range and precipitation. First, a regional comparison was carried out for six regions over the globe. The most significant change probably is an increase of the relative share of heavy rainfalls on the monthly precipitation totals in the greenhouse gas only experiment (GHG), especially over Central North America in summer and over Southern Asia and the Sahel.

Secondly, patterns of expected climate change derived from the model experiments were used in an optimal fingerprint algorithm for climate change detection. Climate change is detectable in this study for annual means and the amplitude of the annual cycle of near surface temperature and for the annual means of precipitation, but not for the annual cycle of precipitation nor annual means or the annual cycle of diurnal temperature range. A problem with the analysis for DTR is the low coverage in time as well as in space of the available observations. However, caution is called-for in the interpretation of the results presented. The results are still preliminary, and a more detailed analysis of the uncertainties in the detection analysis is needed incorporating inter- and intra-model uncertainties, uncertainties in the observational records and uncertainties in estimating natural variability.

Climate change is detectable in this study for the annual means and the annual cycle amplitude of near surface temperature and the annual means of precipitation.

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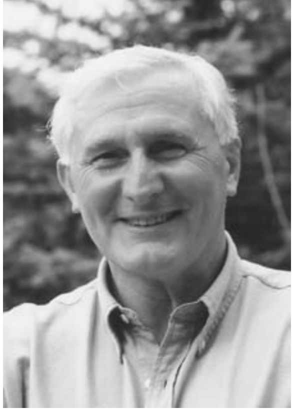
The most significant change probably is an increase of the relative share of heavy rainfalls on the monthly precipitation totals.

SESSION 2

Steve Schneider and Reiner Schnur discuss changes in extreme events.



Communicating Climate Science to Decision-Makers, with Special Reference to the Policy Community

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The Importance of Effective Communication

Virtually every poll that attempts to assess and understand peoples' preferences and concerns and what influences these, clearly underscores the importance of effective communication. Thus it should come as no surprise that the print and television news media, in particular, have a decided influence on society's preferences and concerns, as well as society's understanding of important issues. Simply put, society requires information to make decisions and plan for the future. Yet in order for that information to have societal value, it must first be fundamentally intelligible.

Unfortunately, at a time when concerns about the state of the environment loom large on the political and social fronts, the science community has generally been slow in recognizing and coming to grips with the importance of effectively communicating the results of socially-relevant scientific research to decision-makers, the media, and society at large. In a soon-to-be released summary of a Congressional report known as the "Science Policy Project," the science community is cited as having historically failed to effectively communicate its scientific concerns to Congress and other decision-making bodies in a clear, simple, and understandable manner. The report calls upon the science community to remedy this situation.

Vice President Gore has long called for "clarity" from the science community. In a June 1, 1998 White House Executive Memorandum calling for government regulations to be written in plain language, the Vice President stated that "Clarity helps advance understanding and understanding can help advance trust." More recently, on August 4, 1998, a group of senior scientists announced the creation of an innovative new program to train "scientist communicators" for the future and hopefully improve the flow of accurate, credible scientific information to policy makers and the general public on critical issues of the environment. Supported by a $1.5 million, 5-year grant from the Packard Foundation, the new Ecological Society of America program calls for some of the Nation's leading scientists to become "Aldo Leopold Leadership Fellows" and share their environmental science expertise with local communities, the news media, political leaders, and local, state, and federal policy makers.

In short, effective communication of socially-relevant scientific research is not only essential to the health and well-being of society, but it is arguably as important as the conduct of the research itself.

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Background

It would appear that the one element common to most polls designed to assess people's sensitivity, concerns, and attitudes toward a range of issues is that a large majority of the U. S. citizenry seems to be genuinely concerned about the state of the environment. However, when polled about their primary sources of information and understanding of environmental issues, the majority of people cite the print and television news media (see, for example the July 28, 1998 poll, "The Impact of the Fall 1997 Debate About Global Warming on American Public Opinion" by Krosnick and Visser, Resources for the Future, Washington, DC). Given the short, punchy and simple style of communication, as well as the ubiquitous and convenient access to these forms of media, one can at least partially understand why most people have come to rely on them as their primary sources of environmental information.

On the other hand, one could also make a reasonable case that the preferences cited above are at least partially linked to the science community having historically frustrated large segments of society by rendering science virtually unintelligible and therefore, seemingly unrelated to peoples' day-to-day lives and concerns. Perhaps Albert Flagg, a local developer from Tucson, Arizona said it best when, at a recent climate workshop in Tucson, following a morning of scientific presentations, he stated "although it's clear that the climate issue is an important one, I understood nothing that was said this morning."

The science community having historically frustrated large segments of society by rendering science virtually unintelligible and therefore, seemingly unrelated to peoples' day-to-day lives and concerns.

I submit that to some unknown extent, the science community has abdicated its responsibility, either by oversight or indifference, to effectively and substantively communicate socially important and relevant scientific results to society. The net effect is that society has come to rely almost exclusively on those outside of the science community, those who, ironically, are least familiar with science and the "scientific method," to communicate to the public at large, either by default and/or opportunity, those elements of science that appear to have important societal implications or consequences.

Not surprisingly, similar preferences are also evident in Congressional circles, given that Congress is by-and-large a representative cross-cut of American society. However, unlike society at large, Congress and the White House have been quite vocal about their frustration with the seeming inability or indifference of scientists to communicate science effectively to decision-makers. In a soon-to-be-released summary report on the Congressional "Science and Policy Project," Congress explicitly calls upon the science community to communicate science more effectively to policymakers, using plain, clear language devoid of scientific jargon.

One of the key shortfalls of this state of affairs is that there is presently a formidable and ever-growing body of "scientific mythology" that has crept into the national psyche, some of which has no doubt been purposeful, driven by an assortment of self-interested political agendas. And this growing scientific mythology has served to greatly confuse the public. It is not uncommon to hear frequent cries within the science community that the results and implications of important scientific research have often been mis-stated, mis-characterized, or worse, completely misrepresented, by television and print media. It cannot be said that

such characterizations of scientific results are necessarily born purely out of poor reporting practices, malice, or questionable motives, but are more likely due to a fundamental lack of understanding or familiarity with the science at hand.

While I am not suggesting that every scientist should be required to become a more effective communicator, I maintain that those scientists who venture out into public and policy forums have a special obligation and responsibility to effectively communicate scientific results to those audiences in clear and simple terms. Unfortunately, failure to effectively communicate science in public and policy forums is not without risk. Ineffective communication can often have lingering repercussions that can carry an inordinately high cost — unwittingly breeding confusion and frustration, and raising legitimate questions of social relevance and cost.

Suggestions to the Science Community for More Effective Communication of Science to a Broad Array of Decision-Makers, Particularly in the Policy Arena

It's Not Academic

Making use of a "recycled" academic presentation in a policy setting will likely result in confusing the issue at hand and having your audience turn away completely out of frustration with your inability (or in the worst case, indifference) to effectively communicate using clear and simple language. Lack of clarity breeds suspicion and frustration and is a recipe for trouble.

Customize Your Presentation

Select visual aids to suite your audience. A scientific presentation before a policy audience, for example, will require an investment of time and energy in preparing your presentation and associated graphics. Use individual figures, charts, tables, etc., to convey a single message or idea. Keep visual aids simple, uncluttered, easy to read, and easy to understand. Do not assume that your audience understands any specific visual aid, but rather, walk your audience through the meaning and significance of your visual aids. Mine your visual aids for all of their richness, content, and significance, as this is your responsibility not the audience's.

Engage in a Conversation

Think of your presentation as a short conversation.

Present Your Key Messages or Findings Up Front

From a policy perspective the audience is especially interested in one's key messages or findings and why they are important. It's especially important in a policy setting that you present your key conclusions or "bottom line messages" right up front.

Do Not Engage in Prescribing Policy

A thoughtful and carefully crafted presentation, pitched at the appropriate level, will greatly facilitate bringing forth the policy implications and relevance of the research. Inform the policy process but do not prescribe policy, as this will likely be taken to mean that you are promoting an agenda and not relating the results of your research in an objective, "scien-

Those scientists who venture out into public and policy forums have a special obligation and responsibility to effectively communicate scientific results to those audiences in clear and simple terms.

tific" manner. Prescribing policy will likely render yourself, as well as your scientific results, suspect. It may also result in casting some suspicion on the motives of those who may have sponsored your presentation.

As a case in point, as recently as July of 1998, there were calls in some Congressional quarters for drawing a sharp distinction between education and advocacy activities on the part of certain federal agencies, the latter activity being illegal and potentially carrying severe budgetary consequences. A July 17, 1998 version of House Report 105-610 of the Veterans Administration/Housing and Urban Development and Independent Agencies Appropriations Bill for 1999, the bill that governs Congressional funding to research agencies such as the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA), stated: "While the Committee recognizes the importance of educating the public on environmental issues, there can be a very fine line between education and advocacy of an issue. The Agency (the Environmental Protection Agency) and the CEQ (White House Council on Environmental Quality) are thus directed to refrain from conducting educational outreach or informational seminars on policies underlying the Kyoto Protocol until or unless the Protocol is ratified by the Senate."

Making use of statistical levels of confidence tends to confuse non-scientific audiences, often leaving them with the impression that scientists typically have little or no confidence in their results, when in fact, this is often not the case.

Although this particular language was later amended on July 23, 1998, the general sentiment remains that agencies should pay close attention to the line between education and advocacy. The Congressional Record of July 23, 1998 (Page H6219) states that "Assuming adoption of the amendment (the amendment altering the above language), I would still encourage the EPA and the CEQ to pay close attention to the line between education and advocacy and stay on the right side of that line."

Adopt a Simple, Qualitative Method of Expressing Confidence or Certainty, or the Lack of It

Most people and most decision-makers do not necessarily think "scientifically." Making use of a rigid, statistically-derived confidence level of 95%, for example, as a criterion for expressing confidence, or the lack thereof, for various conclusions, projections, observations, etc., has little or no counterpart in the realm of policy, business, and the day-to-day lives of most people. Outside of the scientific community, many policy- and business-related decisions are routinely made with little or no reference or adherence to any degree of statistical certainty or confidence. Making use of statistical levels of confidence tends to confuse non-scientific audiences, often leaving them with the impression that scientists typically have little or no confidence in their results, when in fact, this is often not the case. Although a lack of clarity often breeds suspicion, people understand and accept the notion of uncertainty. Make use of a qualitative means of expressing certainty, uncertainty, confidence, etc., such as giving "betting odds."

"Debate" is a Loaded Word

A scientific debate in non-scientific circles is unlikely to be a contest of intellects and perspectives where reason prevails. Engaging in a so-called "debate," especially in a political setting, can often be fraught with any number of unforeseen pitfalls. I submit that the word "debate" is presently hard-wired into the American psyche to mean that 50% of the people in question are on one side of an issue and 50% are on the other side. In other words, a

"debate" implies that there can only be two sides to an issue, and that the sides are implicitly divided equally, and the issue is therefore, very much undecided. Thus, the mere act of agreeing to engage in a debate, before any words are uttered, is often interpreted to mean that the issue at hand is still very much undecided.

In addition, once involved in a "scientific debate," one may find oneself pitted against individuals with training in public relations, and well-versed in the art of making effective use of short, punchy sound-bites, and engaging in political theater. Unless one is similarly skilled and experienced, one may find oneself in a very awkward situation that could have serious, unforeseen consequences.

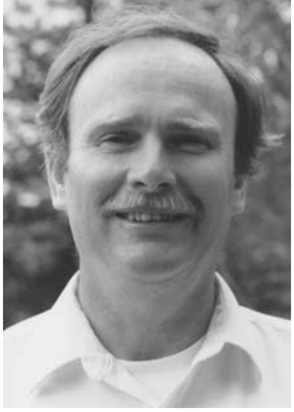
With few exceptions, the general public, policy-makers, and other decision-makers are unfamiliar with the "scientific method." In particular, the policy community, for example, has little or no understanding of, or sensitivity to, the debates and disagreements that routinely occur in the peer-review and publication processes, as fundamental components of the "scientific method." In other words, most people outside of the science community are unaware of the fact that through the processes of scientific peer-review and publication, most published ideas have already survived intense scrutiny and debate at the hands of those who have the training and background to genuinely evaluate the scientific merits, or lack thereof, of one's conclusions and results. I contend therefore, that the real scientific debate has already occurred during the processes of peer-review and publication in respected scientific journals. Consequently, engaging in subsequent "science" debates outside of scientific circles is likely to result in public confusion, not clarification.

The real scientific debate has already occurred during the processes of peer-review and publication in respected scientific journals.

Although calls for a "scientific debate" appear reasonable at first glance, and often elicit notions of fair play and a democratic process in the eyes of many outside of the scientific community, the reality of the situation is far different. Few onlookers to a such a debate are in a position to be able to judge the scientific merits of anyone's case. Consequently, and unfortunately, all too often a so-called "scientific debate" played out in a public or policy forum produces little more than sound bites and confusion. Under the circumstances, a so-called "scientific debate" is scarcely more than political theater. And all too often invitations to engage in a such a debate are really invitations to engage in political theater surrounded by seasoned actors. Thus we must weigh the merits of engaging in such debate very carefully.

Conclusions

While I am not suggesting that improved communication of socially important and relevant scientific results will likely result in immediate or sweeping improvements in understanding of key environmental issues among decision-makers, the media, and the general public, clarity is, nonetheless, a requisite first step in facilitating understanding and trust. Nor is there any reason to suppose that improved communication will necessarily influence politically-entrenched, self-interested, or agenda-driven viewpoints. The science community must also be careful to resist undue political pressures from all sides.



A Canadian Perspective on Extremes

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Canada is subject to a variety of natural hazards and disasters. An historical survey of Canadian disasters shows that 44% are weather or climate related, that almost one-third of all disasters have occurred at sea, and that 80% of those were weather related. A closer examination of these disasters in the past two decades, however, shows that all of Canada's costliest natural disasters in recent years have been weather related. The top ten insured losses reported in Canada are:

Eastern Canada Ice Storm	1998	$2 billion (+)
Saguenay floods	1996	$500 million
Red River flood	1997	$500 m
Calgary hailstorm	1991	$360 m
B. C. snowstorm	1996	$200 m
Winnipeg floods	1993	$160 m
Edmonton tornado	1987	$149 m
Calgary hailstorm	1996	$140 m
Winnipeg hailstorm	1996	$120 m
Saskatoon hailstorm	1994	$100 m

All of Canada's costliest natural disasters in recent years have been weather related. For the third consecutive year, estimated losses to the Canadian economy from storms and dry weather are expected to exceed $3 billion dollars.

Losses in Canada have been increasing and have reached record levels in 1998. This year, likely for the third consecutive year, estimated losses to the Canadian economy from storms and dry weather are expected to exceed $3 billion dollars (Ice Storm 1998 losses are already in excess of $2 billion).

Natural disasters are the extreme events that result when natural hazards and social vulnerability coincide to create major disruptions. The costs Canadians incur from such events are a function of our adaptive decisions. Unsafe conditions result from a number of social forces which are rooted in relative access to utilities, economic resources and the nature of economic and political decisions. The costs of natural disasters can be broken down into social, environmental and economic costs.

Social Costs

In terms of social costs the following statistics give some indication of the overall magnitude:

Transportation

- Decreasing trend of weather related aircraft accidents from approximately 60/year in 1985 to less than 20/year since 1992

- Though there have been few fatalities, there have been a significant number of weather related railway accidents averaging 20-40 per year, however, 100-120 occurred in 1990 and 1991
- Typically 300-400 weather-related marine accidents each year (note: 1990 was the worst of the past 10 years with slightly less than 500 weather-related marine incidents)
- Major road accidents result mainly from wet conditions, followed by ice, snow, slush, and mud. In 1992, weather-related road accidents resulted in 298 fatalities, over 23,000 personal injuries, and over 72,500 property damage incidents.

Deaths
Canadians occasionally die as a result of atmospheric hazards. Most deaths occur as a result of cold. In the past decade, however, the number of deaths from cold has shown a gradual decrease, while those resulting from other atmospheric causes (e. g., lightning) have remained fairly constant.

Dislocation
Dislocation during and as a result of the hazard, job loss, business loss customer loss

Health costs
Health costs, including loss of access to medicine and medical services, and psychological stress

Environmental Costs

- pollution of the environment through the release of waste and chemicals into the environment during the natural hazard (septic tanks, chemical storage and manufacturing facilities, etc.)
- loss of habitat and food for wildlife and wild fowl
- dislocation of wildlife and wild fowl populations

Economic Costs

There are two fundamental economic costs associated with natural hazards — adaptive costs and impacts, response and recovery costs. Adaptive costs are those associated with protection, reduction of vulnerability or risk, education, and research. These costs are difficult to estimate and little research has been devoted to increasing our understanding of these costs. One preliminary estimate of Canadian adaptation costs suggests that $13.7 billion is spent annually; however, this is likely an underestimate of actual costs.

Impacts, response and recovery costs are those incurred when protection fails, no adaptive response is taken, or the affected systems are maladapted and, therefore, cannot deal with the anomalous stress accompanying the natural hazard. Some examples for Canada include:

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Forest fires

- Forest fires can have a direct impact due to loss of natural resources (unclear how to account for these losses as fire is an essential part of the natural ecological cycle), cost of fire fighting, loss of buildings and associated infrastructure, and evacuation costs.

- The annual area burned suggests an upward trend with 1995 being by far the worst year with over 7 million hectares burned, followed by 1989. This year (1998) seems headed to reach a similar, if not greater number, with warm and dry conditions creating ideal burning conditions across most of western and central Canada.
- All provinces incur costs related to fire management (annual costs peaked in 1995 at over $450 million). Over the past decade, Ontario spent over $1 billion, more than any other province.

Hydro Companies

- Weather-related costs are highly variable as indicated by those for Ontario Hydro which has annual weather-related costs ranging from zero to $3 million, and averaging $1.4 million/year.
- Ice swelled power lines to three times their size and toppled steel transmission towers as if they were paper clips during the ice storm of 1998. The weight of the ice over the Ottawa-Carleton region was estimated at 3.7 trillion tonnes (75,000 Titanics). More than 120,000 km of transmission and distribution lines — enough to circle the globe three times — were pulled down by the weight of the ice and by falling trees and branches. The damage in eastern Ontario and southern Quebec was so severe that major rebuilding, not repairing, of the electrical grid had to be undertaken.

In the ice storm of 1998, more than 120,000 km of transmission and distribution lines — enough to circle the globe three times — were pulled down by the weight of the ice and by falling trees and branches.

Opportunities arising as a result of natural disasters include job opportunities and economic benefits associated with clean up, repair and retrofitting.

Recent Weather-Related Natural Disasters in Canada

By far the worst catastrophe in 1996 was the flooding and mud slides in Quebec's Saguenay River valley in mid-July — Canada's first billion dollar plus natural disaster. On July 18, a huge storm curving up from the Caribbean stalled over Eastern Canada. In under 36 hours, the storm produced the largest overland deluge in Canada this century — an amount equivalent to a two-month flow over Niagara Falls. With the soils already saturated as a result of two weeks of rain, a surge of water, rocks, trees and mud was triggered, killing ten people and forcing 12,000 residents to flee their homes. The scale of the tragedy was staggering. Many of the region's roads and bridges and delivery systems for power and water simply disappeared. Including insured and uninsured losses and indirect costs to the economy, total losses have been estimated as being in excess of $2 billion.

Last year, it was the Red River that reeked havoc on the people of Manitoba. Red River valley residents are accustomed to seeing the river rising in the spring — in fact the Red River valley sees some order of flooding on average of once every two years. The 1997 spring flood, however, was the highest waters rose in the past 150 years. Once again a combination of events, this time snow, snowmelt, rain, and saturated soils brought flood waters to the Red. In Canada alone, impacts, response and recovery costs from this natural disaster exceeded $450 million.

Than came 1998 and the storm from hell. From late Sunday, January 4 to Saturday, January 10, freezing rain lashed eastern Ontario and southwestern Quebec (and the northern New England states) before heading into Canada's Atlantic provinces. In Ontario, the storm

dumped 85 mm of freezing rain on Ottawa, 73 mm on Kingston, and 108 mm ravaged Montreal and parts of the province's south shore. By January 18, 25 Canadians in the storm's path were dead.

Emergency crews worked around the clock responding to reports of trees pulling down power poles and ice toppling transmission pylons. Close to 110,000 homes, farms and businesses ("customers") in eastern Ontario were without electricity. In Quebec, 1.4 million customers lost power — translating into roughly three million people or half the province's population. At the height of the storm (January 9), more than 10% of Canadians were without electricity.

The worst of the devastation stretched more than 300 kilometers from Ottawa/Carleton through Montreal to Drummonville, Quebec. Scores of municipalities and townships in the affected area declared a state of emergency and the federal government mobilized over 15,500 soldiers in the biggest peacetime deployment of the Canadian Armed Forces in the country's history.

Freezing rain during the six-day episode ranged from 60-100 mm (2-4 inches). Previous major ice storms in the regions deposited 30-40 mm of ice tops — about half the thickness from the 1998 ice storm. During Ice Storm 1998, it rained ice on six days, but not continuously. The number of hours of freezing rain and drizzle was in excess of 80 — again, nearly double that experienced during previous "major" events. Adding to this, no appreciable melting occurred during the six days.

In the past ten years in Canada, the list of ravaging weather catastrophes seems endless with extreme weather becoming the norm with more climatic oddities and freakish weather. According to the Insurance Bureau of Canada, it all began on July 21, 1987 (the "Black Friday" tornado in Edmonton was Canada's second worst with 27 deaths and nearly $250 million in damage) and the number of multi-million dollar losses from weather disasters has been on the rise ever since.

Should we be concerned by all this climatological mayhem? It is not long term change in the mean that threatens us most — we have the capacity to adapt to such slow change. But small changes in the mean can cause large changes in extreme weather events and thus cause more natural disasters. This is the chief cause for concern.

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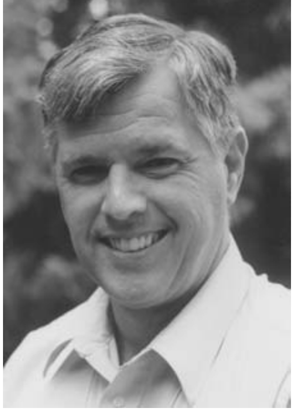

U. S. Disasters and Climate Research

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Scientific analysis of climate and weather extremes requires valid data streams and high confidence predictive models. Climate and meteorological researchers may want to consider a new record of climate change — the presidential declaration of major disaster or emergency. Such a data source represents about a 45 year timeline of human dimensions of weather extreme impacts. This analysis aims to provide introductory guidance and information filtering capacity to those who might incorporate this type of data into their climate models.

The record of presidential declarations of major disasters or emergencies represents about a 45 year timeline of human dimensions of weather extreme impacts.

From 1953, the year the first presidential disaster declaration was issued, to September 1989, the United States never experienced a disaster costing more than $1 billion in federal relief funds. Since September 1989, the U. S. has suffered at least ten major disasters, each much exceeding $1 billion in federal relief costs. From May 1953 through May 1997 there have been some 2,000 gubernatorial requests for presidential declaration of major disaster or emergency. About one-third of these requests were denied by presidents from Eisenhower to Clinton. Of the 1,299 requests approved in that interval, about 90% were for major disaster and 10% for emergency. Weather events are the primary incident cause of no less than 1,216 of these declarations (major disaster and emergency combined). This represents 93.6% of the total declarations issued by the president (More can be found on these records in University of Delaware Sea Grant, Sylves, 1998).

Note that each declaration is issued to a state which has within it one or more counties declared as disaster sites. Some disaster events (e. g., hurricanes, blizzards, floods, etc.) affect more than one state and so generate multiple declarations for a single event. Declarations embody hard evidence of natural disaster in many instances. However, they do not necessarily correlate with insured disaster losses or various state and local losses ineligible for federal disaster relief. There is a record of county inclusion in the 44-45 year history of presidential declarations, but it is beyond the scope of this study to analyze that record. An analysis of declaration information is published in a 1996 book (Sylves, 1996, Ch. 2, 26-45).

These are the fundamental definitions of major disaster and emergency used in presidential declarations:

Major Disaster means any natural catastrophe (including any hurricane, tornado, storm, high water, wind-driven water, tidal wave, tsunami, earthquake, volcanic eruption, landslide, mudslide, snowstorm or drought), or, regardless of cause, any fire, flood, or explosion in any part of the U. S., which, in the determination of the president, causes damage of

sufficient severity and magnitude to warrant major disaster assistance under the Stafford Act to supplement the efforts and available resources of states, local governments, and disaster relief organizations in alleviating the damage, loss, hardship, or suffering caused thereby.

Emergency means any occasion or instance for which, in the determination of the president, federal assistance is needed to supplement state and local efforts and capabilities to save lives and to protect property and public health and safety, or to lessen or avert the threat of a catastrophe in any part of the U. S.

There is usually a $5 million federal spending cap on "emergencies." Incidents which require more than $5 million in federal assistance ordinarily require a request for "major disaster." "Emergency Actions" involve emergency work essential to save lives and protect property and public health and safety performed under Section 306 of the Disaster Relief Act of 1974 (U. S. Senate, Bipartisan Task Force, 1995).

Disaster Frequency and Costs

Disasters and emergencies impose numerous kinds of costs on the individual, the society and the nation. Monetary or economic damages are an explicit part of disasters and emergencies, but disaster's social and human costs may also be severe. From a social perspective, the loss of human life and the suffering resulting from loss of life, loss of home, security, etc., has the potential to be greater than economic loss. Moreover, environmental costs in terms of the loss of land and ecosystems in general, or more accurately the change in land and ecosystems (which may never be truly restored), are also part of the metric of disaster loss. In recent years, as the number and magnitude of disasters and emergencies has increased, these forms of disaster cost have risen as well.

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Why the increase in disaster incidence and cost? Natural cycles, weather anomalies, plate tectonics associated with seismic and volcanic activity, El Niño currents, and arguably "global warming's" impact on climate change and sea level rise have been a few of the factors challenging scientific investigation and prediction. *The Wall Street Journal* reported that the reinsurance industry is concerned because its members get the loss claims from violent storms, floods, and other natural disasters (Fialka, 1997). Thomas Karl, a scientist at the Commerce Department's National Oceanic and Atmospheric Administration, thinks more losses will loom as the temperature rises. In a *Scientific American* article he is quoted as predicting that killer heat waves, severe droughts, more cloudbursts and heavier snowstorms in northern climates, and rising ocean temperatures will result. Knutson, Tuleya, and Kurihara are among a body of scientists who posit from modeling experimentation that a CO_2-warmed climate may increase hurricane intensities, making them more destructive once they make landfall (Knutson, et al., 1998).

Compounding natural factors are social factors.

1) Increasing Population Density: The population of the U. S., increases every day with many more people living in metropolitan areas and more development attending that settlement.
2) Increased Settlement in High-Risk Areas: More people reside in coastal areas which are hurricane prone or seismically active areas, because of favorable climates and the avail-

ability of work or they live in regions or areas vulnerable to natural disasters. Pielke, Jr. and Landsea document the increasing vulnerability of U. S. coastal areas stemming from population growth, immense and continuing development, and the cost of property at risk. They demonstrate that annualized U. S. hurricane damage is escalating even if there is little evidence of increase in hurricane frequency over the past 50 years for the Atlantic and Gulf regions (Pielke, Jr. and Landsea, 1998).

3) Increased Technological Risks: Large-scale use of hazardous technologies which did not exist in prior centuries have added to disaster risk and vulnerability (Petak, 1985).

Vitousek, et al., claim that between one-third and one-half of the land surface has been transformed by human action while the carbon dioxide concentration in the atmosphere has increased nearly 30% since the beginning of the Industrial Revolution, thus making it clear that "we live in a human-dominated planet" (Vitousek, et al., 1997, pp. 494).

Likewise, development in flood plains, the destruction of wetlands, the over-farming of land, deforestation owing to development, the paving of roads and parking lots, etc., have all served to increase the run-off from heavy rainfall. In addition, heavy engineering of flood control works sometimes lulls communities into a false sense of security and encourages inappropriate risk-taking. Ever-expanding sewer systems raise the probability that sewage plants will be inundated by flood water and that systems will back-up, thus flooding basements and low-lying areas.

Development in flood plains, the destruction of wetlands, the over-farming of land, deforestation owing to development, the paving of roads and parking lots, etc., have all served to increase the run-off from heavy rainfall.

SESSION 2

The following points are illuminating:

- Every state is at risk from flooding, and some 21,000 communities face significant flood risk. The 1993 Midwest Floods resulted in $15-20 billion in losses. Annual flood damage is on the order of $4 billion.
- In 1992, Hurricane Andrew resulted in $30 billion in damages in Florida and Louisiana. More than 50 million Americans live near hurricane-prone coastlines.
- Every state is at risk from wildfires, though California and the Northwest are especially vulnerable. More than 9,000 homes have been consumed by wildfire in the last decade. The record year for wildfire damage was 1996 when some 84,200 fires burned an estimated 5 million acres. The previous record was 1994 when 79,000 wildfires were reported (U. S. Senate, Bipartisan Task Force, 1995, Sec. 1, pp. 1-16).

In examining disaster laws and policy one needs to understand that they reflect greater overall trends in politics and policy making in the United States. Although disasters and emergencies represent unique events, government's involvement in them is similar to the way it has approached many other policy issues. This is true with respect to the nature of events as well as the governmental actions that have been designed to deal with them (Sylves, Chap. I, 1996).

One could make the case that government's increased involvement in disasters is a manifestation of a larger trend towards *greater public sector responsibilities.* The U. S. has undergone a tremendous growth in terms of the size and scope of government. For example, in 1992 public expenditures were approximately $2.5 trillion, while in 1942 they were only

about $47 billion. In addition to spending more money, the government has also chosen to address more issues and problems while allocating more money to them.

American disaster policy has demonstrated *greater involvement by the national government* relative to the state and local levels. The federal government began to play a more active role is disaster policy during the 1930s and enacted legislation in 1950 which established a basic framework for disaster policy under which the federal government was allowed to direct and coordinate efforts in the event of severe disasters. That function, and role of the federal government, was expanded through the 1970s and in 1979, the U. S. Federal Emergency Management Agency (FEMA) was established to consolidate and coordinate those actions. The creation of FEMA was a clear sign that the issue of disasters had become a permanent addition to the federal government's policy agenda.

The history of government involvement in disasters also reveals the *reactive nature of policymaking* in this domain. Major disasters have often served as stimulants of change and reform in disaster policy. This was evident in the early history of disaster policy when aid was tied to specific legislation passed after every event. Today mega-disasters requiring enactment of large supplemental appropriations compel Congress to enact new post-disaster laws. Through these and other measures federal disaster policy is expanded and clarified.

American disaster policy has demonstrated greater involvement by the national government relative to the state and local levels.

Great disasters call for an immediate public sector response since the public wants something done immediately. In the same manner, however, these events do not sustain long-term public or governmental interest and involvement. Once action has been taken or normalcy returns, the public and government tend to move on to other matters.

Nevertheless, ever-present *incremental* decision making also continues. Past policies become entrenched and they provide the foundation for future government activity. Incrementalism is a pervasive, limiting force in governmental disaster-relief policy making. Moreover, public sentiment may deter public officials from pursuing alternative policies, those that stress more preventive strategies. People may not want the government to enact stronger and more effective building codes and zoning laws if they are believed costly or intrusive, as might occur when government prohibits development in hazard-prone areas.

Disasters which used to cost thousands or millions of dollars and affect only scores of victims now sometimes cost many billions of dollars and affect many thousands of victims. In 1994, the federal cost of disaster relief was $4.4 billion. In that year there were 16,272 locally declared disasters. Of this total, 299 became state declared emergencies, and 37 were federally declared. Generally, 2-3% of local disasters that require significant assistance by a state are declared emergencies by the governor. In Fiscal Year 1995, there were 28 presidentially declared disasters, the federal cost of which was over $3 billion. The trend continues. During just the first six months of 1996, 43 major disaster declarations were issued. In contrast, in 1978 there were "just" 9 declarations [National Emergency Management Association, 1996].

Under major disaster or emergency circumstances, states receive from FEMA a match supported subsidy (75%/25%) to provide supplemental assistance to individuals and families adversely affected.

After a Presidential Declaration has been issued several types of federal disaster assistance become available. Under major disaster or emergency circumstances, states receive from FEMA a match supported subsidy (75%/25%) to provide supplemental assistance to individuals and families adversely affected. This is defined as *individual assistance*. While some forms of individual assistance such as temporary housing are managed exclusively by FEMA, others such as loans to businesses and farm loans are managed by the Small Business Administration (SBA) and the U. S. Department of Agriculture (USDA) respectively. FEMA also provides *public assistance* to state and local governments or certain private, not-for-profit organizations, on a 75/25 cost sharing basis, to help restore public services and to provide infrastructure support. Note, that the president has the authority in law to increase the federal share of the match beyond 75%, and up to 100%, when he determines this to be necessary. Extra money comes to states and localities through FEMA's Hazard Mitigation Assistance program. This helps state, local and other eligible parties lessen or avert the threat of future disasters through funding projects aimed at reducing or eliminating future disaster vulnerability (Sylves, Chap. I & II, 1996).

Table 20
Coastal vs. Non-Coastal States by Type of Disaster Incident, Number of (Presidential) Declarations*, and Federal Disaster Relief Spending in constant 1994 dollars from May 1953 to May 1997.**

* Presidential declarations for majors disasters ands emergencies.
** Spending in 1994 U. S. Dollars. Disasters which have occurred within the last ten years still incur spending, so dollar amounts are a snapshot as of May 1997.

Type of Disaster	Abbr	Presidential Declarations: Coastal States	Presidential Declarations: Non-Coastal States	Coastal Percent	Federal Spending: Coastal States	Federal Spending: Non-Coastal States	Coastal Percent
Flood and Tornado	A	68	36	65%	$ 1,105,103,913	$ 451,694,072	71%
Coastal Storm	C	9	0	100%	$ 102,871,105	$ -	100%
Drought	D	25	18	58%	$ 145,552,127	$ 120,647,279	55%
Earthquake	E	15	2	88%	$ 7,675,577,301	$ 2,631,147	100%
Flood	F	368	260	59%	$ 6,795,592,722	$ 2,944,804,031	70%
Hurricane	H	92	2	98%	$ 7,305,445,209	$ 14,077,768	100%
Typhoon	J	37	0	100%	$ 737,178,709	$ -	100%
Dam/Levee Break	K	1	1	50%	$ 7,545,257	$ 2,038,123	79%
Mud Landslide	M	1	0	100%	$ 4,785,660	$ -	100%
Fishing Losses	P	4	0	100%	$ 12,866,371	$ -	100%
Fire	R	24	5	83%	$ 511,098,583	$ 11,247,332	98%
Snow/Ice	S	77	20	79%	$ 938,437,645	$ 228,229,598	80%
Tornado	T	72	40	64%	$ 359,671,464	$ 132,651,284	73%
Volcano	V	3	1	75%	$ 73,496,152	$ 3,119,943	96%
Severe Storms	W	64	28	70%	$ 1,442,765,599	$ 282,518,716	84%
Toxic Substances	X	5	2	71%	$ 47,363,510	$ 353,410	99%
Human Cause	Y	4	2	67%	$ 322,825,230	$ 35,601,815	90%
Other	Z	12	1	92%	$ 19,420,310	$ -	100%
Total		881	418	68%	$ 27,607,596,865	$ 4,229,614,518	87%
Grand Total			1299	combined		$ 31,837,211,383	combined

There are 30 coastal states and 20 inland states. Therefore, coastal states represent three fifths of the total states. If territories and the District of Columbia are included, coastal jurisdictions jump to 39 and inland to 21. Presidential disaster declarations run from the first in May 1953 to a total of 1,299 in June 1997 with major disasters and emergencies included together. Recall that emergencies are very similar to major disasters except their

relief spending is capped at $5 million in federal expenditures. Constant dollar base year of 1994 was used since this was the last year of data in the original data set supplied by FEMA. Deflators were used for federal spending in the years 1995, 1996 and 1997 in order to incorporate cost data up to June 1997. Recall that federal relief spending is for FEMA and predecessor agencies only and excludes other federal disaster relief programs not funded by the President's Disaster Relief Fund (*e. g.*, Small Business Administration disaster loans, U. S. Department of Agriculture crop insurance, Housing and Urban Development disaster aid, Department of Transportation disaster aid, etc.)

Hurricanes

One would expect coastal states to experience hurricanes more frequently than inland states. Consequently it is no surprise that the 39 coastal jurisdictions secured 92 declarations for hurricane to only 2 for inland states (see Table 20). What is remarkable is that more than $7.3 billion in federal relief went to coastal jurisdictions representing about 27% of the $27.6 billion total constant dollars spent by the federal government for all coastal state disaster relief over the interval 1953-1997. Correspondingly, that $7.3 billion is 23% of the $31.8 billion spent on all presidentially declared disasters in the interval. About half of the $7.3 billion was for Hurricane Andrew's devastation alone. Remember, Hurricane Andrew relief spending extends well beyond June 1997 and continues at this writing. Only $14 million went to inland states for post-hurricane disaster relief from mid-1953 to mid-1997.

Moreover, hurricane and typhoon declarations together bring the 44-year total of these primary incident declarations to 131 (129 coastal and 2 inland) or about 10% of all declarations for major disaster and emergency. If the 37 declarations for typhoon are added to the hurricane totals, federal relief spending for hurricane/typhoon declarations jumps to over $8 billion or nearly 30% of all coastal state constant dollar federal disaster relief and 25% of all constant dollar federal disaster relief.

An extraordinary share of the nation's disaster declarations and federal disaster relief spending flow from hurricanes and typhoons. It is worth emphasizing that for the 44 year period, 30% of all coastal state constant dollar federal relief spending is for hurricane/typhoon and 25% or a quarter of the constant dollar federal relief spending is for hurricane/typhoon. Admittedly, about half of each of these percentages are attributable to Hurricane Andrew alone. However, should the nation again suffer Andrew-scale hurricane damage, the percentages of post-hurricane/typhoon relief will be skewed even more dramatically upward.

An extraordinary share of the nation's disaster declarations and federal disaster relief spending flow from hurricanes and typhoons.

Figure 89 shows that peak hurricane/typhoon federal constant dollar relief funding occurs from 1989-94, with another sizable spike in the 1995-97 interval. Hurricane Andrew in 1990 and Hurricane Hugo in 1989, respectively produce the largest peaks. Note that the spending on all of these declarations is a June 1997 snapshot with funding on each event assumed to be telescoped back into the year of the declaration. Clearly, this record is not a perfect compendium of hurricane/typhoon frequency or impact, but it does represent an artifact of human dimensions of natural disaster hurricane/typhoon impact which can be factored into climate change research and modeling.

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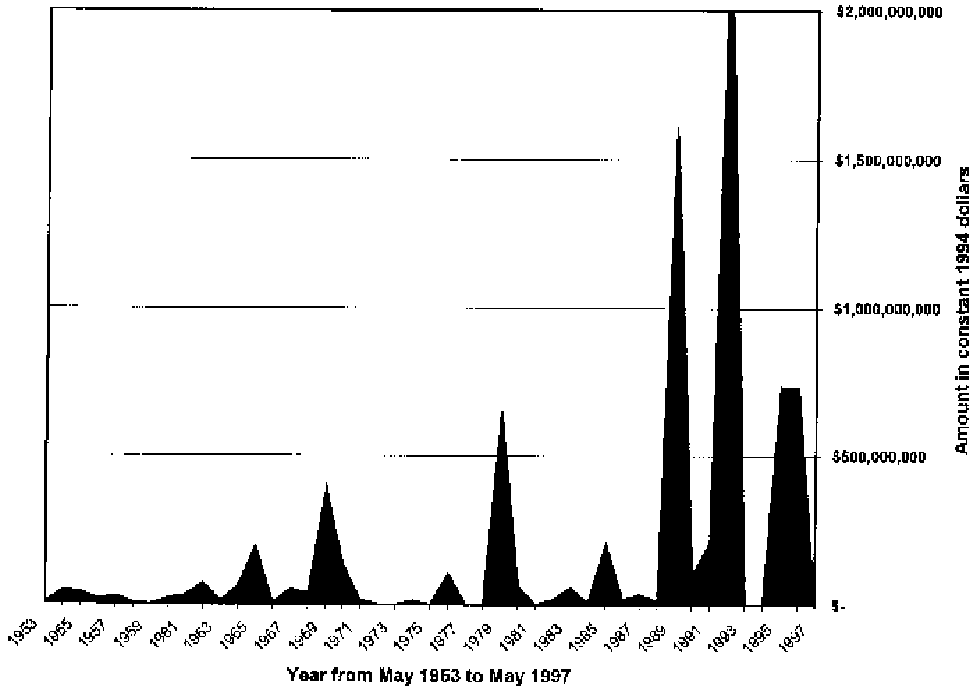

Figure 89
Total Combined Hurricane and Typhoon Disaster Spending in 1994 Constant Dollars, May 1953 to May 1997.
All dollars represent federal disaster relief funding from the President's Disaster Trust Fund, the main repository of federal disaster relief budget authority.

Floods

Table 20 demonstrates that inland and coastal states frequently experience flooding. Recall that Table 20 data is for presidential declarations of major disaster and emergency. Not all floods win such designations. Consequently the data used in this study are not a perfect meteorological record, but instead constitute a political-administrative record of presidential declarations in which flood is the primary incident in the declaration. The Tornado and Severe Storm section below employs a category FEMA labels "Flood and Tornado." Consequently, there are about 104 "Flood and Tornado" declarations excluded in this flood-focused section which are taken up later. Moreover, the table is based on "primary" incident frequency not on second or third order incidents. For example, floods are often a consequence of hurricanes and typhoons, as well as coastal storms. However, this section only concerns the narrow category in which "Flood" is the primary incident. A great number of other primary incidents beside "flood" include flood devastation.

In spite of these qualifications, the number and constant dollar 44 year damage totals for floods is incredibly high. No less than 628 of the 1,299 declarations in Table 20 are for primary incident "flood." With three fifths of the states in the coastal category, 59% of the declarations are directed to coastal states. Therefore coastal states do not win a disproportionately large number of declarations for "flood" primary incident disasters. Coastal states

do secure 70% of the federal disaster relief constant dollar funding for primary incident "flood" declarations in the 44 year interval. This again, is not disproportionately large, especially when one considers that the territories, all coastal jurisdictions, are included in the coastal state set.

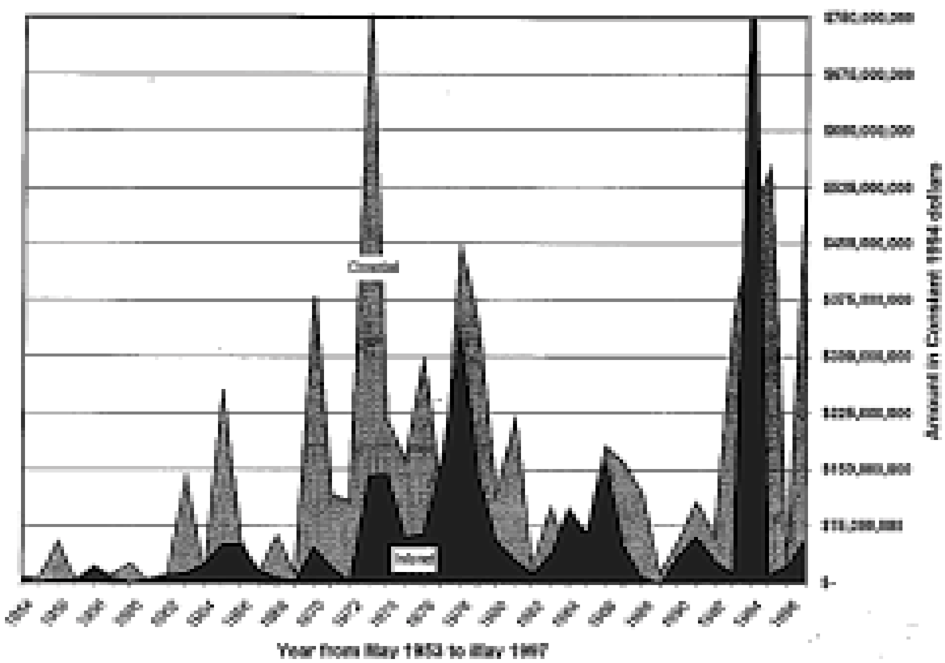

Figure 90
Total Flood Disaster Spending by the Federal Government in 1994 Constant Dollars, Coastal vs. Inland States, May 1953 to May 1997
The peak year is 1994, the year of the Great Midwestern Flood, which mainly impacted inland states. The next highest peak is for coastal states in 1973. The pattern of constant dollar flood relief suggests that 1993-95, 1996-97, 1973, and 1978-80 were periods of tremendous flood disaster loss for the nation as a whole. Remarkably, coastal and inland states show huge increases in flood disaster relief almost consistently from 1991-97 with the exception of 1996.

As before, federal relief spending is in 1994 constant dollars and percentages are calculated from Table 20. It is remarkable that for coastal states, primary incident flood declaration federal relief spending is 24.6% of all coastal federal disaster relief from 1953 to 1997. Primary incident flood declarations for coastal states yields 21.3% of all federal disaster relief over the same period. By contrast, inland state primary incident flood declaration federal disaster relief is a mammoth 69.6% of all inland federal disaster relief from 1953 to 1997. However, non-coastal (inland) state primary incident flood declaration disaster relief is only 9.2% of all federal disaster relief for the 44 year era.

These findings suggest that flood disasters, in terms of primary incident declarations, generate a substantial but modest share of coastal state constant dollar federal disaster relief. Table 20 reveals that hurricane and earthquake generate higher sums of constant dollar

Inland state primary incident flood declaration federal disaster relief is 69.6% of all inland federal disaster relief from 1953 to 1997 but only 9.2% of all federal disaster relief for the 44 year era.

federal disaster relief for coastal states than do floods. However, for coastal states, the combined "flood" and "flood and tornado" primary incident categories produce a constant dollar relief amount greater than the individual quake and hurricane categories. The main point is that flood is a paramount form of disaster damage for coastal states, but in the aggregate, hurricane and earthquake rival and exceed flood in terms of constant dollar federal relief expenditures for the 44 year interval. For inland states, flood is far and away the most costly disaster agent if share of constant dollar federal disaster relief spending is considered.

Tornados and Severe Storms

Unlike earthquakes and hurricanes, tornados and severe storms do not automatically trigger presidential disaster declarations. Tornados have occurred in virtually all 50 states, but most in the central and eastern U. S. Coastal states are as vulnerable to tornado and severe storm damage as inland states are.

The United States experiences more tornado activity than any other country. The National Weather Service (NWS) considers tornados to be nature's most violent weather phenomenon. Some tornados have been clocked with wind speeds well over 200 mph. Maximum tornado winds are extremely difficult to measure because metering equipment is usually destroyed by the force of the winds themselves. Tornados have resulted in an average of 80 deaths and 1,500 injuries each year. For 1995, there were 30 tornado fatalities. This was less than half of 1994's total of 69, and significantly lower than the 30-year average death toll of 73. However, tornado fatalities soared in 1998, with Florida suffering over 200 alone for that year. The number of fatalities from tornados is in part attributable to tornado unpredictability and rapid speed of onset. Climate researchers may want to incorporate the longitudinal record of tornado devastation into their analyses.

The United States experiences more tornado activity than any other country. The National Weather Service (NWS) considers tornados to be nature's most violent weather phenomenon.

Table 20 contains the primary disaster incident category "flood and tornado." The separate "flood" primary incident category in the table has been previously discussed. The umbrella term "flood and tornado" means a tornado was the primary incident and flood may have been a coincident manifestation of the disaster or that flood and tornado together represent the primary incident. FEMA does have a "tornado" primary incident category. As before, we are discussing primary incidents in Table 20. It must be understood that tornados may be secondary or tertiary disaster agents in other disasters. For example, many hurricanes spawn tornados as secondary agents of devastation. So the "flood and tornado" category captures some, but not all tornadic damage included in presidentially declared major disasters and emergencies.

Table 20 reveals that coastal states have received 71% of federal disaster relief (constant 1994 dollars) expended for "flood and tornado" primary incident declarations. This is not highly disproportionate given that coastal states are 60% of all states and 65% if coastal states and territories are combined (as they are in Table 20). Primary incident "flood and tornado" declarations for coastal states yield only 4% of total coastal federal disaster relief (constant 1994 dollars) and are 7.7% of all coastal state declarations for the 44 year period. Primary incident "flood and tornado" declarations for inland states yields a 10.7% share of

total inland federal disaster relief (constant dollars) and are 8.6% of all inland state declarations for the same period.

Relatively speaking, "flood and tornado" in the context of this analysis is substantially equal for inland states and coastal states vis-a-vis declarations issued. Moreover, the share of federal disaster relief (constant dollars) attributed to "flood and tornado" primary incident declarations for coastal and inland states is similar. What is noteworthy is the 10.7% share of total inland federal disaster relief (constant dollars) stemming from "flood and tornado" primary incident declarations.

Severe thunderstorms are also cause for concern, especially because tornados and highly damaging winds are sometimes produced from them. Thunderstorms affect relatively small areas when compared with climate events such as hurricanes and winter storms. The typical thunderstorm is 15 miles in diameter and lasts an average of 30 minutes. Nearly 1,800 thunderstorms are occurring at any moment around the world. Despite their small size, all thunderstorms are dangerous. Every thunderstorm produces lightning, which kills more people each year than tornados. Heavy rain from thunderstorms can result in flash flooding. Strong winds, hail, and tornados are also dangers associated with some thunderstorms. The National Weather Service reports that of the estimated 100,000 thunderstorms that occur each year in the U. S., only about 10% are classified as severe.

"Severe Storms" are a category of primary incident in the disaster declaration process. Table 20, as explained, presents all dollar amounts in 1994 constant dollars. Table 20 makes it clear that total federal disaster relief for primary incident "severe storms" ($1.73 billion) actually exceeds total federal disaster relief for "flood and tornado" primary incidents ($1.56 billion).

In the matter of coastal vs. inland states, coastal states win a disproportionately larger share of federal disaster relief funding (84%) than do inland states for severe storms. However, when it comes to the number of declarations issued for "severe storms" primary incidents, coastal and inland states have balanced shares (70%), with coastal states winning only 5% more than their proportional representation. Nevertheless, another primary incident category must be considered and that one is "Coastal Storm."

Table 20 shows that for the 9 "coastal storm" primary incident declarations, unsurprisingly all went to coastal states. If the $102 million in constant 1994 dollar federal disaster relief for these declarations is added to the coastal "severe storm" primary incident federal disaster relief category, coastal state storm disasters yield about $1.55 billion in federal relief for the interval studied. Total "storm damage" federal relief then jumps to about $1.83 billion and the coastal state share of that amount is 84.7%. Also, if the 64 coastal state "severe storm" declarations are combined with the 9 "coastal storm" declarations, coastal states jump to 72.3% of all "storm" declarations, an amount which begins to exceed its proportional share.

This pattern of coastal state predominance is even more pronounced if "snow/ice" primary incident declarations are considered. Table 20 shows that coastal states won 79% of all

Nearly 1,800 thunderstorms are occurring at any moment around the world. Despite their small size, all thunderstorms are dangerous. Every thunderstorm produces lightning, which kills more people each year than tornados.

snow/ice declarations issued in the 44-year period. Since no territories have won declarations for primary incident snow/ice (all are in tropical or sub-tropic zones), the pool of coastal states stands at 30 or 60% of the 50 states. About $1.17 billion in federal disaster relief (constant 1994 dollars) has been paid out on snow/ice primary incident declarations. Coastal states received 80% of this $1.17 billion sum.

If "coastal storm," "severe storm," and "snow/ice" primary incident declarations are combined, there were 198 declarations or 15.2% of the total 1,299 pool of declarations. Coastal states secured 150 declarations, or 75.6% of the 198 declarations of the pool. For these 150 declarations, coastal states received (again in 1994 constant dollars) about $2.5 billion, or of the approximately $3 billion spent in this pooled category. This means coastal states secured 83% of the constant 1994 dollar federal disaster relief funding expended for "coastal storm," "severe storm," and "snow/ice" primary incident disaster declarations issued from mid-1953 to mid-1997. In other words, coastal states have won a disproportionately large share of declarations, and federal disaster relief, for the combined "storm-snow-ice" categories.

Coastal states have won a disproportionately large share of declarations, and federal disaster relief, for the combined "storm-snow-ice" categories.

SESSION 2

Table 20 discloses that there have been 43 declarations for drought from May 1953 through May 1997 generating about $266 million in federal disaster relief. Drought spending is included in Figure 91 and is not differentiated from "flood and tornado," "tornado," "severe storm," "coastal storm," and "snow/ice." A key qualification is that these data do *not* include U. S. Department of Agriculture drought disaster assistance program spending.

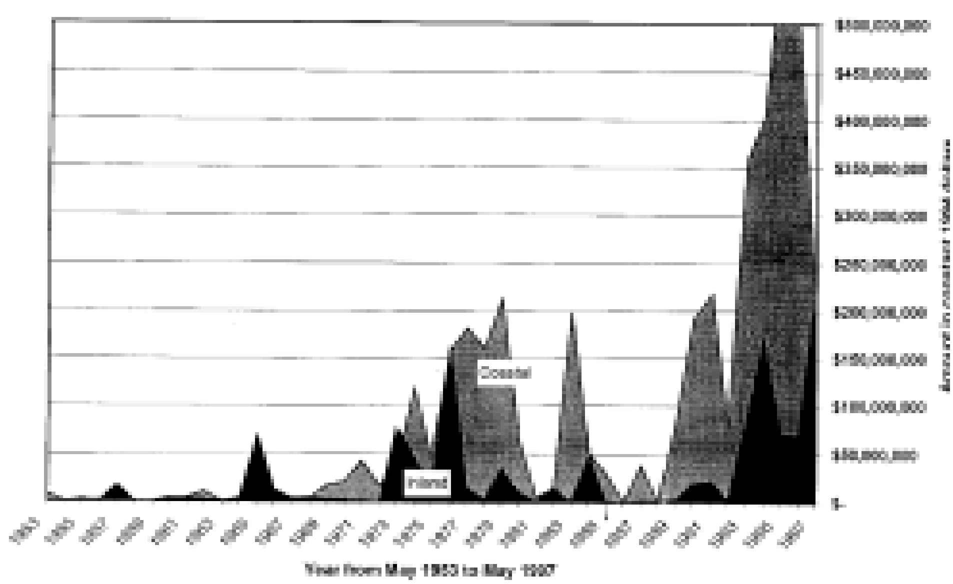

Figure 91
Total Severe Storm/Tornado* Disaster Spending in 1994 Constant Dollars, Coastal vs. Inland States, May 1953 to May 1997
*Severe Storm/Tornado includes the following disaster categories: Flood and Tornado, Tornado, Severe Storm, Coastal Storm, Snow/Ice, and Drought.

Figure 91 is one of the clearest indicators of the ramp up in federal disaster relief costs and incidents this researcher has encountered. Coastal states especially have experienced huge run-ups in federal disaster relief spending for the primary incident Figure 91 disaster types included from 1989 through 1997.

Conclusions

Presidential declarations of major disaster and emergency offer a promising source of weather event human loss data for climate researchers. Efforts should be made to correlate temperature and precipitation extremes research with the archive of declarations available from 1953 to the present. It is possible to control for some types of social factors in conducting this research (*e. g.*, use of constant dollars, incorporation of census data regarding population change variables and settlement patterns for decadal periods, assessed valuation of property by county and state over time, etc.)

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Coastal states especially have experienced huge run-ups in federal disaster relief spending for the primary incident Figure 91 disaster types included from 1989 through 1997.

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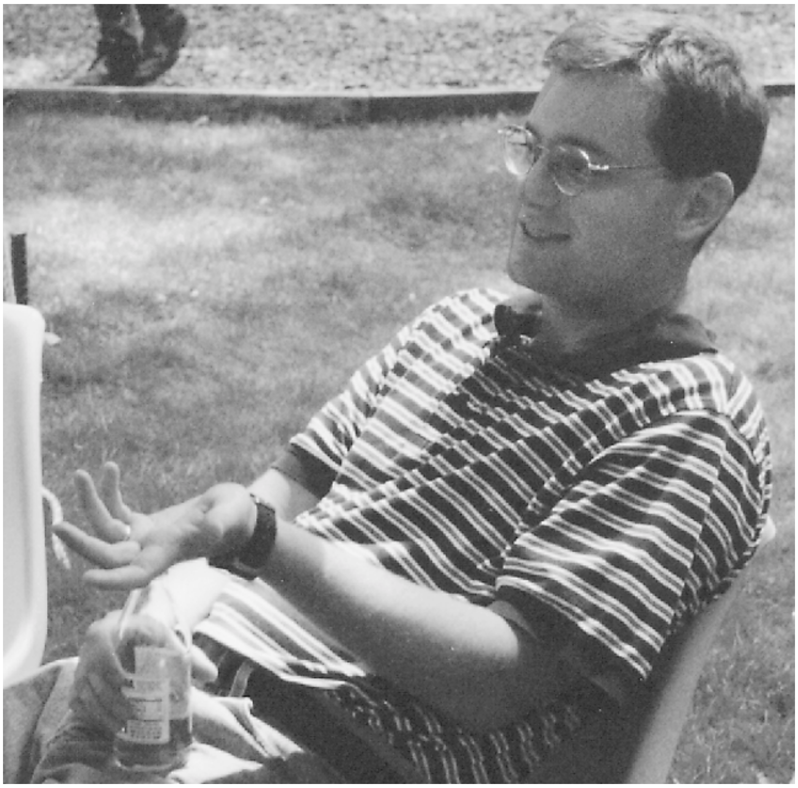
Presidential declarations of major disaster and emergency offer a promising source of weather event human loss data for climate researchers. Efforts should be made to correlate temperature and precipitation extremes research with the archive of declarations.



Roger Pielke, Jr., in group discussion on societal aspects of climate extremes.

Changes in Climatic Extremes: Towards an Assessment for the Australian Region

Peter Whetton
Climate Impact Group
CSIRO, Atmospheric Research
Victoria, Australia

In many areas, the effects of climate change will be felt directly through changes in the frequency and intensity of extreme events. This has been very evident to members of CSIRO's Climate Impact Group as we have endeavored to serve the climate change data needs of impact assessment work in Australia in recent years. For example, in a current project, assessing the risk to transport infrastructure due to climate change, seven of the eight key climatic factors identified as critical were extreme weather events (flood rains, extreme high temperatures, dust storms, storm surges, etc.). In this presentation, I consider extreme event simulation in some current CSIRO climate modeling, the key uncertainties which apply to these results, and a methodology for dealing with uncertain climate change information in impact assessment.

Simulating extreme weather events in a realistic way puts high demands on climate modelers. Current global climate models (GCMs) have a horizontal resolution of around 200-500 km, which is not fine enough to adequately simulate climate at the regional to local scale. This is true for mean climate, and more particularly for extreme events, which are often highly localized in nature. Furthermore, models of this resolution cannot simulate the intensity of smaller scale circulation features associated with extreme weather, such as tropical cyclones. Use of much finer resolution for global models is limited by computer power, but techniques exist for economically obtaining finer resolution model data. The method being used at CSIRO is to run a fine resolution regional climate model nested in a GCM for the region of interest.

The method being used at CSIRO to study extreme events is to run a fine resolution regional climate model nested in a GCM for the region of interest.

Recently, CSIRO has undertaken an experiment with the CSIRO regional climate model, DARLAM (McGregor, 1997), nested in the CSIRO coupled atmosphere-ocean GCM. Two stages of nesting were used to give a simulation with resolution of 125 km over the Australian region and one with 60 km resolution over the more populous southeast corner of Australia. The simulation covered the period 1961-2100 using observed CO_2 forcing to 1990 and a mid-case scenario of increasing CO_2 to 2100. This simulation period (140 years) is much longer than that typically used in high resolution modeling, and is very suitable for the analysis of more rarely occurring extreme events. To date, the 60 km run has been analyzed for patterns of change in extreme daily rainfalls, the frequency of frosty and hot days, and the frequency of very dry or very wet seasons. For these climatic components, DARLAM's current climate simulation (1961-1990) is quite realistic, and much superior to

that of the host GCM. DARLAM is also able to simulated tropical cyclone-like vortices (Walsh and Watterson, 1997) and work has begun on analysis of simulated change in their characteristics in the 125 km run.

The model simulates very marked decreases in the frequency of frosty days in winter (days with a minimum temperature of less than 0°C) and marked increases in the frequency of hot days in summer (defined as days with a maximum temperature of 35°C or over). In the example shown (Figure 92, southeastern New South Wales) all but four of the first 40 winters (1961-2000) have at least 10 frosty days, but there are no winters after the year 2050 with at least this many frosty days. The frequency of hot days nearly doubles by late in the simulation period. These changes in extremes are primarily a consequence of the simulated mean warming (1.7°C by 2050). Changes in the standard deviation of temperature are very small relative to the change in the mean, and have little impact of the occurrence of extremes.

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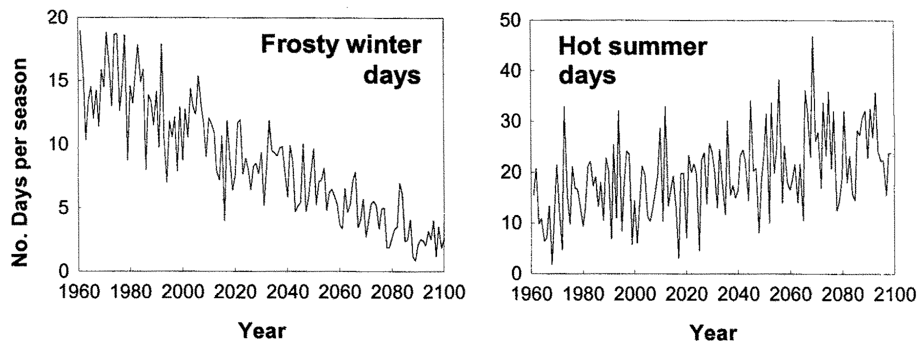

Figure 92
Simulated extreme temperature occurrence in southeastern New South Wales.
Frosty days are defined as days with a minimum temperature less than 0°C, and hot days as days with maximum temperature greater than 35°C.

Increases in the frequency of days with high maximum temperature may lead to greater heat-stress in humans, livestock, ecosystems, agriculture and building materials; increased bushfire potential; and higher energy demand for air-conditioning. Less frequent frosty days may lead to altered crop-sowing dates to suit a longer frost-free season; reduced frequency and intensity of frost damage to frost-sensitive crops; reduced quality and quantity of horticultural crops due to inadequate winter chilling for normal bud-burst; reduced dormancy for pests and diseases; and reduced energy demand for heating.

Substantial changes in the frequency of wet years and dry years are also produced. These too are mostly due to simulated changes in mean rainfall, although the effect of changes in variability is more significant than it is for extreme temperature occurrence. Figure 93 shows simulated summer rainfall and frequency of wet years in southern New South Wales. As a result of an increase in mean rainfall of 10%, the frequency of the current one-in-ten year wet summer doubles by 2050.

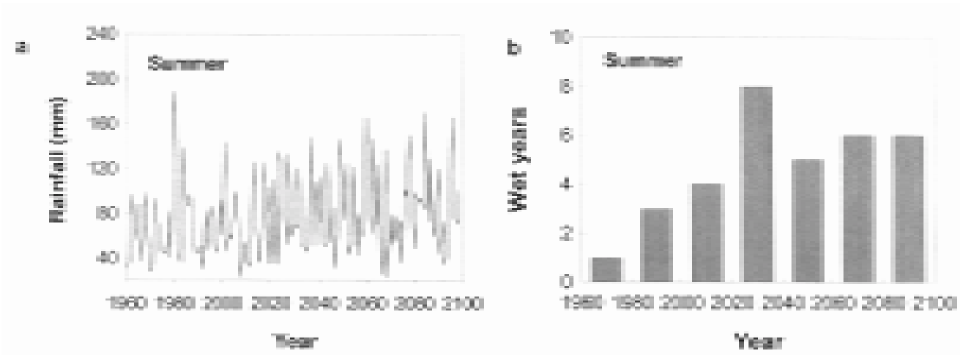

Figure 93
Simulated summer total rainfall and the frequency of wet summers per twenty year period in southern New South Wales.
(Wet summers have rainfall above the 4th wettest summer in period 1961-2000.)

There is a marked increase in the simulated frequency of days of very heavy rainfall, and in the magnitude of daily rainfall events of a given frequency. For example, in some parts of the domain, and in some seasons, the magnitude of the one-in-twenty year event increases by as much as 50% (Figure 94). It is notable that increases in the magnitude of the heaviest rainfall events are commonly simulated even in those areas where mean rainfall decreases. Previous GCM-based studies have observed this tendency in enhanced greenhouse simulations with coarse resolution global climate models (*e. g.*, Hennessy *et al.*, 1997), and it presumably reflects the increased potential of a warmer atmosphere to hold moisture. Increases in the frequency and magnitude of high rainfall events have important implications for agriculture, water and land management, flood control and emergency services.

There is a marked increase in the simulated frequency of days of very heavy rainfall, and in the magnitude of daily rainfall events of a given frequency.

Simulated changes in extremes such as these constitute a plausible scenario of future regional climate change rather than a prediction. Despite the rapid improvement in modeling tools in recent years, regional climate change projection is still affected by various uncertainties. Although it is possible to allow for uncertainties associated with future greenhouse gas emissions and the sensitivity of the global climate system by the use of scaling techniques, less easily quantified uncertainties remain. These include:

- Whether current climate models adequately simulate climate changes related to the El Niño-Southern Oscillation (a major cause of year-to-year rainfall variability over Australia, and elsewhere).
- Whether the pattern of warming at the ocean surface is adequately simulated. Climate (particularly rainfall) in the Australian region is very sensitive to the oceanic response to enhanced greenhouse conditions (through changes in sea surface temperature patterns).
- Whether climate processes at the land surface are adequately simulated. There is evidence that rainfall results are sensitive to the representation of soil and vegetation over the continents.
- That natural climatic variability at the yearly to decadal time scale may partially (or wholly) mask enhanced greenhouse changes in climate for some decades into the future both in the model and in the real world. This variability introduces significant uncertainty into the projection of regional climate change, particularly for extreme event occurrence.

- Whether changes in sulfate aerosol pollution (which would occur mainly in the northern hemisphere) would affect Australian climate. This has not been included in the CSIRO simulations for southeastern Australia as yet, although based on GCM results from some other modeling centers, and a very recent CSIRO GCM study, the impact is not expected to be large.

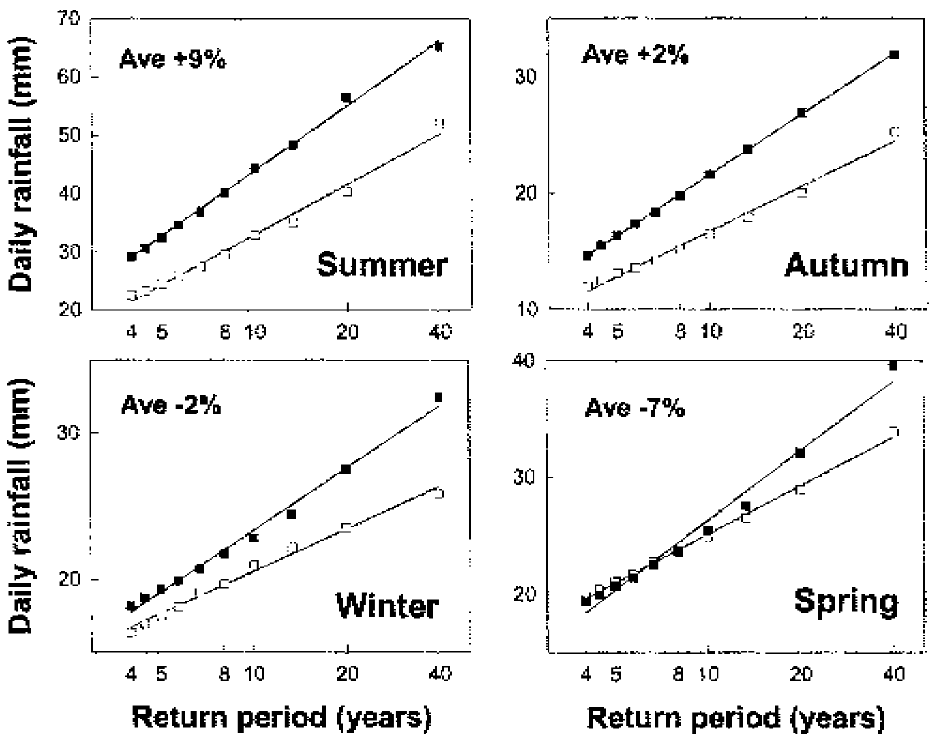

Figure 94
Simulated heavy daily rainfall return periods averaged over southwestern New South Wales.
Open squares are for the present (1961-2000) and solid squares are for 40-years centered on 2050. Changes in mean seasonal rainfall (Ave) are also shown.

It may be best to consider climate change and its impacts in a risk assessment framework in which the probability of various future climates are estimated and the risk of exceeding key impact thresholds is assessed.

SESSION 2

Although the current high resolution simulation is the most realistic available at present for Australia for assessing possible changes in extremes, further revisions to regional climate projections may be expected in the future as new simulations are undertaken using improved models. Although in time we expect uncertainties to be significantly narrowed, it is inevitable that climate change information will continue to encompass a range of possible changes in climate. Therefore, it may be best to consider climate change and its impacts in a risk assessment framework in which the probability of various future climates are estimated and the risk of exceeding key impact thresholds is assessed. This allows information on future climate change to be readily incorporated into planning for the future while making due allowance for uncertainty. However, quantifying the probability of various climatic states (which in many cases will need to be defined in terms of the frequency and intensity of

various extreme events) represents a major challenge. The risk-based approach to climate change impact assessment is currently being researched in CSIRO (Pittock and Jones, 1998).

Acknowledgments
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Quantifying the probability of various climatic states (which in many cases will need to be defined in terms of the frequency and intensity of various extreme events) represents a major challenge.

Jenni Evans discusses modeling of extreme events with Roger Pulwarty.

Steve Schneider illustrates an upward trend to Michael Schlesinger and John Katzenberger.

Roger Street makes a point while Rick Sylves and Lennart Bengtsson look on.

Changes in Annual Extremes under Equilibrium and Transient Climate Change

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This paper briefly describes changes in annual extremes surface properties (2-meter screen temperature [shielded or "screened" from the elements] and precipitation) simulated in an equilibrium climate change simulation and an ensemble of 3 transient climate change simulations performed with Canadian Centre for Climate (CCC) GCM2. The equilibrium change experiment (Boer et al., 1992) was performed with a version of GCM2 that is coupled to a mixed layer ocean model (McFarlane et al., 1992). The transient change experiments for 1850-2100 (Boer et al., 1998a,b) were performed with a version of GCM2 that is coupled to a modified version of the GFDL Modular Ocean Model and a thermodynamic sea-ice model (Flato et al., 1998). The effective CO_2 and aerosol forcing prescription used in these transient simulations is described by Mitchell et al. (1995). The manner in which the direct aerosol effect is implemented in the model is described in Reader and Boer (1998). Further details on the model and output from both experiments are available from the CCCma web site (http://www.cccma.bc.ec.gc.ca). A detailed description of the changes in extremes in the equilibrium experiment is given by Zwiers and Kharin (1998; here after "ZK"). A manuscript describing changes in the transient experiments is in preparation (Kharin and Zwiers, 1999; here after "KZ").

This paper briefly describes changes in annual extremes surface properties (temperature and precipitation) simulated in an equilibrium climate change simulation and an ensemble of 3 transient climate change simulations.

Extreme value analysis methodology

Extreme value analyses were conducted with samples of annual extremes of screen temperature minima and maxima, annual maximum 24-hour precipitation amounts. Analyses have also been performed on annual maximum 1000 hPa wind speed, but these are not discussed here (see ZK and KZ for details). Samples of 20 annual extremes were obtained from the control and doubled CO_2 runs that comprise the equilibrium change experiment. Samples of 63 annual extremes were extracted from the transient experiments for each of three 21-year windows representing 1975-1995, 2040-2060 and 2080-2100. (Each member of the ensemble of three simulations provides a sample of 21 annual extremes for each of the time windows, so that there is a combined sample of 63 annual extremes for epoch.) Temperature and precipitation extremes were derived at run time by sampling these fields at every time-step of the simulations. Wind speed extremes, on the other hand, were derived from values archived at 12-hour intervals. Statistical estimates derived from the latter are therefore subject to some additional uncertainty because sampling is incomplete.

The generalized extreme value (GEV) distribution was fitted to the annual extremes at each grid point using the method of L-moments (Hosking, 1990). Return values were estimated

for various return periods. A bootstrapping method was used to determine the uncertainty of the derived estimates. Because the greenhouse-gas signal is small in precipitation and wind-speed, an attempt was made to use a spatial smoothing approach to decrease the uncertainty of estimated changes in return values under equilibrium and transient climate change. This worked well for precipitation because its variations are not strongly coherent spatially. However, we were not able to reduce the uncertainty of the estimated changes in wind speed extremes with this technique. Methodological details are given in ZK and KZ describes further refinements.

Extremes in the equilibrium control climate

The validation of extremes simulated by climate models is difficult on a global scale because reliable gridded observed data comparable to that produced by the model is scarce. We therefore limited our comparison on the global scale primarily to NCEP-NCAR reanalysis data for 1979-95 (Kalnay et al., 1996). We also compared simulated extremes over Canada with estimates derived from Canadian temperature data (about 160 stations with an average record of about 50 years) and precipitation data (approximately 500 stations with an average record of about 25 years; Hogg and Carr, 1985).

The validation of extremes simulated by climate models is difficult on a global scale because reliable gridded observed data comparable to that produced by the model is scarce.

SESSION 2

Screen Temperature

The model did a credible job of simulating 20-year return values of daily minimum temperature. In comparison with the reanalysis, extremes over polar and northern land masses are well simulated, while those over western Europe are somewhat too warm. The model reproduced return values estimated from Canadian station data quite well in the southern half of the country, but model derived estimates tend to be 5˚C to 8˚C too low over northern Canada.

The model's ability to simulate extreme warm temperatures was more difficult to assess on a global scale because of a problem in the reanalysis that led to some excessively warm temperature extremes (see ZK and references therein). In comparison with Canadian station data, the model tended to under-simulate extreme warm temperature by about 5˚C.

Precipitation

Estimated 20-year return values of daily precipitation in the equilibrium control climate is displayed in Figure 95. A corresponding map derived from NCEP-NCAR reanalysis is not displayed because the latter does not appear to reproduce observed precipitation variability very well, particularly in the tropics, perhaps because of difficulties associated with model spin-up.

Return values in the tropics and sub-tropics in the model reflect the large-scale divergent tropical circulations of the simulated climate. The locations of the upward (high return values) and downward (low return values) branches of these circulations are easily discernible. The very large simulated return values (more than 200 mm/day) in the western tropical Pacific are likely overestimated since CCC GCM2 simulates more precipitation in the Asian summer monsoon outflow area than is observed.

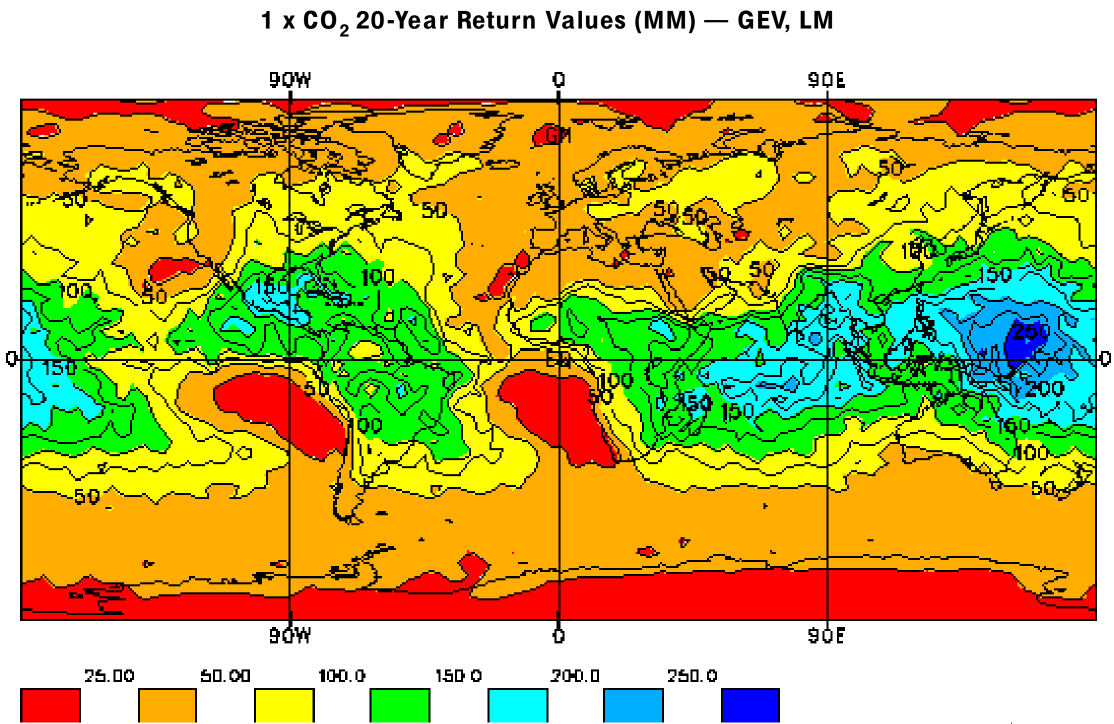

Figure 95
Twenty-year return values for daily accumulated precipitation simulated by CCC GCM2 in the equilibrium control run. Contour interval: 25 mm/day.

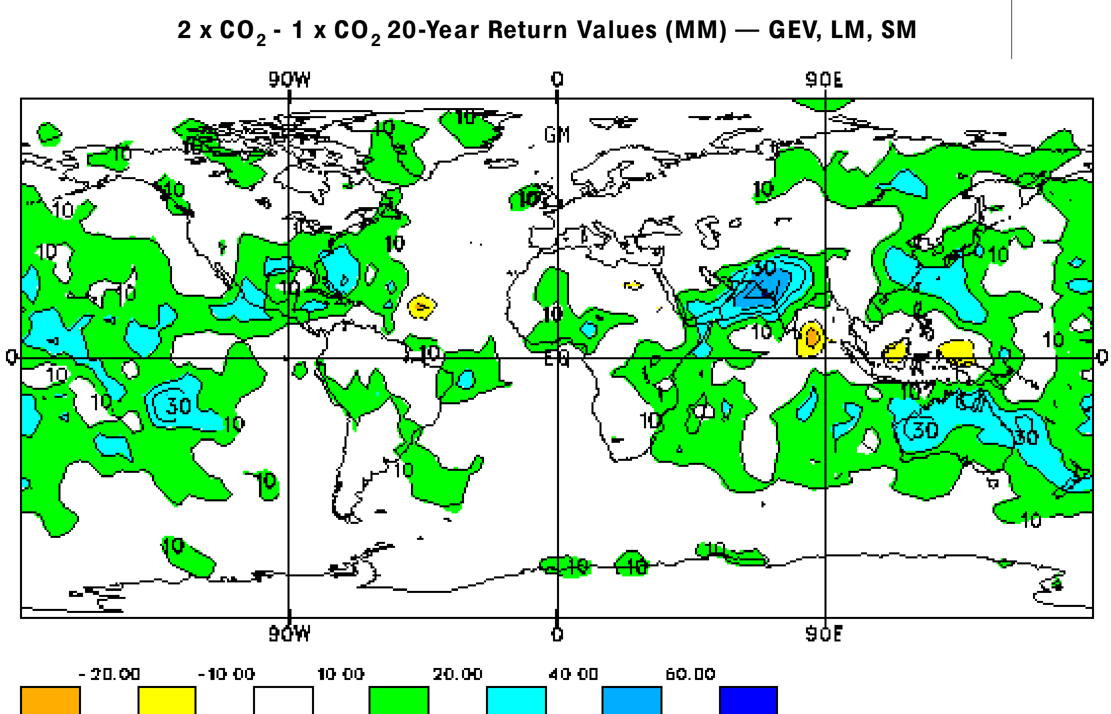

Figure 96
The estimated change in smoothed 20-year return values for daily accumulated precipitation simulated by CCC GCM2 under CO_2 doubling in the equilibrium runs. Contour interval: 10 mm/day.

Estimated return values derived from Canadian station data (not shown) illustrate that, on large spatial scales, the model simulates plausible values over much of Canada. Extremes over Atlantic Canada appear to be underestimated, as are small scale features that are associated with local orography.

Changes under equilibrium climate change

Screen Temperature

The equilibrium change under CO_2 doubling in the estimated 20-year return values of the daily minimum and maximum temperature, $T_{Min,20}$ and $T_{Max,20}$ respectively, are not equal. For example, the global mean change for $T_{Max,20}$ is 3.14°C whereas that for $T_{Min,20}$ is 5.0°C.

The changes in $T_{Min,20}$ and $T_{Max,20}$ apparently occur for a variety of reasons. Over the tropical and temperate oceans both increase by an amount that is roughly equal to the change in the mean screen temperature. This is physically reasonable since screen temperature is largely determined by surface temperature over the oceans.

Elsewhere (over land masses and polar regions) there are changes in both the location and the shape of the screen temperature distribution. Increases in $T_{Max,20}$ over continents (except Antartica) are of the order of 5°C and range up to 10°C. The larger values occur in regions of North and South America and Eurasia which experience a substantial decrease in soil moisture in the simulation. Reduced soil moisture means that maximum surface temperatures are less likely to be moderated by evaporative cooling.

The global mean equilibrium change under CO_2 doubling is an increase of 5.0°C for daily minimum temperature and 3.14°C for daily maximum temperature.

Increases in $T_{Min,20}$ over North America and Western Asia are larger than the corresponding increases in $T_{Max,20}$. This presumably occurs because snow cover is reduced in the warmer world. Increases in $T_{Min,20}$ over Siberia (which remains snow covered in winter under CO_2 doubling) are roughly comparable to the increases in $T_{Max,20}$. Changes in both quantities are also roughly comparable over Africa. Over South America however, increases in $T_{Min,20}$ are smaller than those in $T_{Max,20}$, perhaps because of a decrease in soil moisture and clouds.

Only small increases in $T_{Max,20}$ occur in polar regions which retain some sea ice. Presumably temperature maxima are strongly constrained here by the cold water which is exposed as leads and thus contains melting ice. For the same reasons (increased leads and thinning of the sea ice) large increases are observed in $T_{Min,20}$. This occurs because the atmosphere is in better contact with the ocean in the 2 x CO_2 climate.

Precipitation

Smoothed estimates of the change in the 20-year return values of 24-hour precipitation are displayed in Figure 96. (The smoothing technique used is described in ZK.) The change is positive almost everywhere. The largest increases, over 50 mm/day, is found over the northwest coast of India where there is intensification of the Asian summer monsoon under CO_2 doubling. Globally averaged, 20-year return values increase 9 mm/day (11%) while the daily mean rate increases by only 4% (0.11 mm/day). Over Canada, 20-year return values increase approximately 7 mm/day (14%) which translates in a 50% reduction in the mean waiting time between 1 x CO_2 extreme events in the 2 x CO_2 world. ZK provides more

detail, including an analysis of the change in intensity and frequency of precipitation in the warmer world.

Changes under transient climate change

A similar approach was used to estimate changes in the extremes temperature and precipitation in the transient climate change simulations at the time of CO_2 doubling relative to the present (i.e., 2040-2060 vs. 1975-1995) and at the time of tripling (2080-2100 vs. 1975-1995). Globally averaged changes in the means and the 20-year return values at the time of doubling and tripling in the transient experiment and also in the equilibrium experiment are summarized in the following table. As can be seen, changes at the time of doubling are relatively modest when compared with those for the equilibrium experiment.

	T_{min} (˚C)			T_{max} (˚C)			P (mm/day)		
	$\Delta_{2,tr}$	$\Delta_{3,tr}$	$\Delta_{2,eq}$	$\Delta_{2,tr}$	$\Delta_{3,tr}$	$\Delta_{2,eq}$	$\Delta_{2,tr}$	$\Delta_{3,tr}$	$\Delta_{2,eq}$
Mean	1.93	4.12	3.67	1.79	3.87	3.37	0.03	0.10	0.11
20-yr	2.33	5.13	5.06	1.82	3.94	3.14	6.82	12.27	9.03

Table 21
The change in the global average of the annual mean and 20-year return values of daily minimum temperature, daily maximum temperature and 24-hour precipitation at the time of CO_2 doubling (2040-60; denoted $\Delta_{2,tr}$) and tripling (2080-2100; denoted $\Delta_{3,tr}$ relative to the present (1975-95) as simulated in the CCCma ensemble of transient greenhouse gas plus aerosol experiments (Boer et al., 1998a,b). Corresponding values from an equilibrium change experiment (Boer et al., 1992; denoted $\Delta_{2,eq}$ are also displayed.

Temperature

In general, the pattern of change in the 20-year return values at the time of doubling is similar to that at the time of tripling. Both patterns are also similar to that in the equilibrium experiment, with moderate increases over oceans and larger increases over land masses.

The greatest change in the return values of daily maximum temperature is found in central and southeast North America, central and southeast Asia and tropical Africa where there is a large decrease in soil moisture content. Large extreme temperature increases are also seen over the extremely dry surface of north Africa. In contrast, the west coast of North America is affected by increased precipitation resulting in moister soil and more moderate increases in extreme temperature. There are small areas of decrease in the Labrador Sea and Southern Ocean that are associated with changes in ocean circulation.

As in the equilibrium change experiment, the changes in the return values of daily minimum temperature are larger than those of daily maximum temperature over land areas and high latitude oceans where snow and ice retreat. In a global sense, minimum temperature extremes at the time of tripling are comparable to those under CO_2 doubling in the equilibrium experiment. However, somewhat larger changes are found over land masses and the Arctic while smaller increases in extreme minimum temperatures occur at the margins of the polar oceans.

The greatest change in the return values of daily maximum temperature is found in central and southeast North America, central and southeast Asia and tropical Africa where there is a large decrease in soil moisture content.

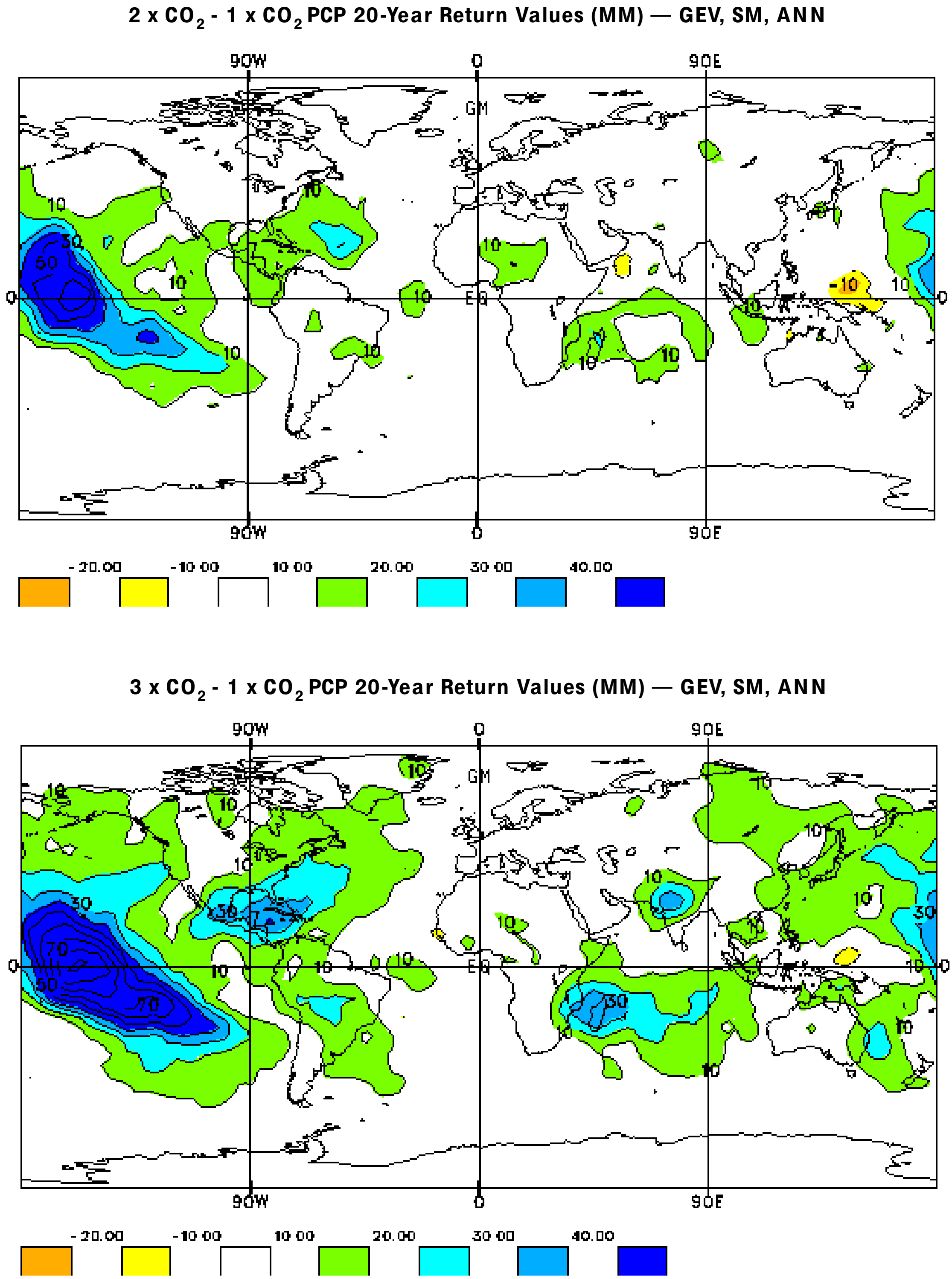

Figure 97
The estimated change in smoothed 20-year return values for daily precipitation in the transient runs under CO_2 doubling (upper panel) and tripling (lower panel). Contour interval: 10mm/day. Zero line is omitted.

Precipitation

Globally averaged, there is little change in the annual mean amount of precipitation at the time of doubling and only a modest increase at the time of CO_2 tripling (Table 21). However, there are substantial shifts in the spatial distribution of precipitation that are associated with a warming pattern that is reminiscent of a gradually strengthening permanent El Niño.

There are associated increases in extreme precipitation almost everywhere (Figure 97). The largest increase in 20-year return values occurs in the tropical Pacific. While changes of less than 10 mm are evident over extra-tropical land masses at the time of doubling, large areas, including eastern North America, are affected by substantially larger increases in the size of these extremes at the time of tripling.

Summary

We have briefly described an extreme value analysis of equilibrium and transient change experiments performed with CCC GCM2, and its coupled version which is known as CGCM1. A limited comparison with Canadian observations and NCEP-NCAR reanalysis data suggest that the model-simulated extremes bear at least some resemblance to those of the real world. There are relatively small differences in extreme temperature changes simulated in the equilibrium and transient runs that are associated with differences in the response of the ocean and sea-ice to the forcing changes. There are relatively larger differences in the extreme precipitation changes simulated in the two experiments which are associated with differences in the mean temperature response, particularly in the tropical Pacific.

There are substantial shifts in the spatial distribution of precipitation that are associated with a warming pattern that is reminiscent of a gradually strengthening permanent El Niño.

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Large areas, including eastern North America, are affected by substantially larger increases in the size of these precipitation extremes at the time of CO_2 tripling.

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SESSION 2

Climate Extremes: Changes, Impacts and Projections

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