The Climate Report™

Vol. 2, No. 1, Winter 2001

In This Issue

Letter From the Editor

Over the past several months, the media has covered the topic of global climate change extensively in form of news paper and magazine articles, TV coverage, radio talk shows, etc. This has been inspired by the recent release of the Third Assessment Reports of three Working Groups of the Intergovernmental Panel on Climate Change (IPCC), which builds upon the past two assessments and includes the latest scientific results during the past five years.

Specifically, IPCC refers to Climate Change as any change in climate over time, whether due to natural variability or as a result of human activity. Climate has changed in the past and is expected to change in the future. Analysis of recent and paleo observational data has indicated a warming world and other changes in the climate system. These changes occur on different time scales and have significant impacts on society. Specifically, for many companies, whose bottom-line is highly vulnerable to climate variability and climate change, climate risk management will become an increasingly important part of their business planning process and an integral component of their long-term business strategy. To effectively manage the impacts of climate variability and climate change, companies must quantify this risk and how it varies over time. This would require access to the highest quality of climate information (e.g., observations and forecasts) and need to understand the science to interpret the information correctly for business decision making. Many questions arise:

1) How and why is our climate changing?
2) How is this change manifested in our day to day weather? What are the implications on regional temperatures, precipitation, extreme events, etc.?
3) What are the uncertainties associated with projections based on observations and global climate models?

In this report we bring you the latest scientific understanding. In the first article, Professor James McCarthy of Harvard University, who serves as the Co-Chair of IPCC Third Assessment Report, Working Group II describes the IPCC process and provides highlights of the latest results outlined in the reports released in February, 2001 by Working Groups I and II. Dr. David Easterling, Principal Scientist at the National Climatic Data Center, and a contributing scientists to IPCC provides a review of the latest scientific results on the impacts of climate change on climate extremes. In the third article, Dr. Kevin Trenberth, the head of the Climate Analysis Section at the National Center for Atmospheric Research (NCAR), describes the latest understanding of how precipitation may be impacted by climate change. Finally, Dr. Paul Epstein, Associate Director of the Center for Health and the Global Environment at Harvard Medical School, describes the latest understanding on implications of global warming for public health.

Maryam Golnaraghi, Editor

Intergovernmental Panel on Climate Change: Third Assessment Report, 2001

By James J. McCarthy

The Scope of the IPCC Third Assessment Report

The Intergovernmental Panel on Climate Change (IPCC) is in the final stages of its Third Assessment Report (TAR). The first assessment was completed in 1990, and the second in 1995-96. The TAR began in October 1997, with approval of the scope of the assessment and the formation of bureaus to oversee the process. As before, three working groups (WG) were formed to assess new information relating to, I) the underlying science of climate change, II) the potential impacts of and vulnerabilities to climate change, and III) strategies to mitigate climate change.

The IPCC Process

Currently about 100 governments participate in the IPCC, and all are invited to propose the names of experts who could serve as authors of these reports. A few thousand nominations were received for the TAR, with supporting documentation listing the nominees' publications in scientific journals. Each working group identified a team of 100 - 200 authors who were given responsibilities for major sections of the reports. In the course of the assessment, additional authors were recruited to round out the teams, resulting in a total of 400 - 600 authors for each WG.

The basis of the assessment is the peer-reviewed published scientific literature. Every effort is made to be thorough, and serious attention is given to disparate results and conclusions in this literature. The assessment involves expert judgment, and to the extent possible, degrees of likelihood are assigned to summary statements, especially those that project future climate conditions and climate impacts.

Each of the three WG reports, in manuscript form equivalent to several hundred to a thousand printed pages, are subjected to two thorough reviews. The first is by experts selected from the original government nomination list plus other known experts. For the second review national coordinating offices in the participating nations select reviewers and coordinate the review process. These two reviews typically involve 300 - 400 experts for each WG.

The full reports are then condensed into a 70 - 100 page manuscript, known as a *Technical Summary* (TS), and it is then further condensed into a 20 page manuscript known as a *Summary for Policy Makers* (SPM). The TS and SPM for each WG (along with a revision of the full report that reflects the earlier government and expert review) are then sent out for a final review coordinated by governments.

Comments from this final review are then used to prepare a revision of the SPM and TS, and a plenary of the WG is convened to consider final approval of the SPM. Typically this session involves about 150 delegates from 100 nations, drawn from each nation's departments and ministries of science. The plenary meets for four days to vet the SPM line-by-line, proceeding to the next line only when all delegates agree to do so. For this current Third Assessment, the plenary for WGI was held in Shanghai (China) in January 2001, that for WG II in Geneva (Switzerland) in February 2001, and that for WG III in Accra (Ghana) in March 2001. The following summary remarks highlight some of the results of WG I and WG II. The outcome of WG III was not known at the time this article was prepared.

Climate history

Many proxies can be used to infer climate conditions in the past, among them the distribution of organisms as determined from the fossil record, changes in the width of tree rings, the abundances of certain isotopes in marine sediments and in ice, etc. During the past two decades many of these techniques have advanced considerably, and multiple approaches are now commonly used to confirm and link different time series of paleo climate data.

Climate has varied in the past, on a wide range of time scales. Only 18,000 years ago a large glacial mass covered much of northern Europe and northern North America. Similar glacial periods have occurred at intervals of about 100,000 to 120,000 years for the last million or more years. Today 85% of the continental ice on Earth is on the continent of Antarctica. Cores that penetrate its full depth have been used to reconstruct a history of temperature and atmospheric composition for key greenhouse gases for the past 420,000 years.

The most readily computed statistic for global climate is Earth's average annual temperature, and it is known most accurately for the last 140 years from instrumental data. As human presence on land has become more extensive, and as ships have crossed the seas more regularly, measuring the temperature of Earth's surface has become more systematic. Analyzing the record of Earth's temperature from the instrumental data, the World Meteorological Organization (WMO) has concluded the following:

- The 1990s were the warmest decade of the last 140 years, and probably the warmest of the last several hundred years.
- Every year within the decade 1990-1999 was among the 15 warmest in the last 140 years.
- The six warmest years over the last 140 years occurred during this past decade.
- The rate of warming during the 20th century was the strongest of any 100-year period.

New findings relating to climate change

The role of WG I is to assess uncertainties in recent climate trends, to attempt to understand the factors responsible for this trend, and to use contemporary understanding of climate to project future changes.

An important aspect of the WMO summary statements about climate in the instrumental era is that they point to a change in globally averaged temperature that appears to be without precedent, in either magnitude or rate, for the last 1000 years. In certain regions there may have been periods during the last 1000 years that were characterized by warmer or cooler climates that rival in magnitude the global average change over the last 100 years. Examples such as the "Little Ice Age" in Europe in the late 1500s and early 1600s or the "Medieval Optimum" around 1000 AD when Viking settlements were established in southern Greenland come readily to mind. However, the reconstruction of climate history from proxies such as those mentioned above lead to the conclusion that these unusually cool or warm periods were highly regional in character, and may well have been offset by opposite trends in other regions. This is highly plausible for landmasses adjacent to the North Atlantic Ocean, since the climate of Europe and southern Greenland are strongly influenced by atmosphere-ocean interactions. Surface water in the northern North Atlantic becomes very cold and salty in regions where sea ice forms, and the sinking of this very dense water serves to draw warm surface water northward from lower latitudes. A reduction in the rate of formation of these dense surface waters has been suggested as an important factor in the conditions that set the stage for the Little Ice Age. In addition, climate in the North Atlantic region is influenced by multi-decadal cycles, such as the North Atlantic Oscillation.

When climate scientists compare trends of the past century with earlier climate periods, two inescapable conclusions are that the current rate of warming exceeds any that can be documented from earlier periods and that the rate of warming is continuing to accelerate. Even if the first of these conclusions could be demonstrated to be incorrect, it is questionable whether analogues in past climate should diminish concern about the potential consequences of a continuation in the recent climate trend. What is different now is that Earth is populated with 6 billion people and the natural and human systems that provide us with food, fuel, and fiber are strongly influenced by climate. Of particular relevance for these systems is the observation that climate change is accelerating, and (as will be seen below) that future change may not occur as smoothly as it has in the past.

The warming over the last century, averaged globally, has been 0.6°C, and the IPCC assessment concludes that this increase in the 20th Century is likely to have been the largest increase of any century during the past 1000 years. Land surface air temperatures have warmed twice as fast as surface ocean temperatures, and this is consistent with land and ocean heat exchange relationships. In addition, nighttime temperatures have increased at twice the rate of daytime temperatures, which is consistent with a change in the radiative forcing of the atmosphere brought about by increasing concentrations of greenhouse gases.

The era of satellite observations began three decades ago, and during this period temperature trends have been monitored for the lower 8 kilometers of the atmosphere. These data show a lower rate of warming than the instrumental record for surface measurement over land and the oceans, especially in tropical and subtropical regions. However, there are many factors, such as stratospheric ozone depletion, atmospheric aerosols, and the El Niño - Southern Oscillation (ENSO) that could contribute to these differences between trends on Earth's surface and in the atmosphere well above the surface.

There are additional corroborating data for an increase in Earth's temperature, including the retreat of mountain glaciers in all non-polar regions, loss of Arctic sea ice (40% of summer thickness since the 1950s), loss of snow cover (10% since the late 1960s), and rising sea level throughout the 20th century. In the last few decades some areas have become ice-free for the first time in several thousand years.

Five years ago the IPCC concluded from recent temperature trends that there is now "a discernible human influence on global climate". The most recent IPCC assessment, which analyzed trends in greenhouse concentrations in the atmosphere and trends in natural forcing from solar activity and volcanoes, concluded that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities." In other words, natural causes in variability in temperature on Earth's surface cannot account for the strong observed warming trend over the last five decades. Observed trends in climate over the last 140 years are, however, consistent with a combination of natural and anthropogenic forcing, with the latter becoming particularly dominant towards the end of this time series. While the component of the change in globally averaged temperature that is attributable to increases in greenhouse gases can be accurately determined for the last several decades, it is not possible to attain comparable accuracy in estimates of the negative radiative forcing arising from the release of aerosols (e.g., volcanoes and certain combustion products such as sulfur dioxide) because of their short residence times in the atmosphere

The projections of future climate conditions in this IPCC assessment also changed relative to the 1995 assessment. New greenhouse gas emission scenarios approved by the IPCC were used to generate a family of temperature projections for the 21st century. A total of thirty-five scenarios were used, and six of them are detailed in the SPM. They vary in their assumptions regarding population growth trends, economic development, and energy efficiency. The temperature projections for 2100 from six illustrative scenarios range from an increase of 1.4°C to 5.8°C. For context, these projected temperature increases in warming are two- to ten-times the observed rate of warming during the 20th century. The upper end of this range is higher than that projected in the 1995 IPCC assessment, in large part because more realistic projections are now being used for atmospheric aerosols. Trends in the last five years indicate that for reasons relating to human health alone, efforts are being taken to reduce sulfur dioxide emissions in rapidly developing areas of the globe that are heavily dependent on the combustion of coal.

An additional finding from WGI that is of profound importance to our understanding of climate change and its impacts relates to variability in climate. Observations over the last 50 years indicate that many aspects of climate have become more extreme, and models project increasing trends in severity and frequency of several of these. A likelihood of greater than 90% is assigned to projections of hotter and longer heat waves over most land areas and more intense precipitation events. A likelihood of 66 - 90% is assigned to increased risk of drought in mid-latitude continental interiors, and increased peak wind and precipitation intensities of tropical storms (hurricanes and typhoons). In addition, a likelihood of greater than 90% is assigned to projections of greater extremes of floods and drought associated with ENSO events, and increased variability in Asian summer monsoon precipitation. [For more information see the article by David Easterling in this issue]

New findings relating to impacts

The effects of recent climate change are now clearly evident in many natural and human systems. The documented changes in Arctic Sea ice cover, both its thinning and its shrinkage during summer, affect polar ecosystems. The shrinkage that is occurring averages 3% per decade for the entire Arctic region, but in the Kara and Barents sea the rate is nearly three times the average. Throughout Northern Hemisphere freshwater ecosystems, the ice-free season is now nearly two weeks longer than it was a century ago, which is consistent with an average annual temperature increase of about 1°C. Increased access for ships is a positive aspect of this trend. During the summer of 2000, for the first time in recorded history, a ship transited the Northwest Passage without touching ice. With summer ice-free conditions in the Arctic expanding poleward, ecosystems will shift accordingly.

Changes in the distribution of species as documented in the fossil record have long been used as an important diagnostic of past climate. For example, a large project in the 1970s known as CLIMAP used the abundances of fossil organisms in marine sediments to reconstruct Earth's climate conditions during the glacial maximum 18,000 years ago. It is well known that on land the distributions of many species and the reproductive behavior (e.g. flowering time and egg laying behavior) of others respond to temperature, and in the past few decades substantial changes in these characteristics have been noted for many species. The IPCC reported that for 80% of the cases, in which recently observed biotic changes could plausibly be linked to temperature, the biotic changes were consistent with changes in regional temperature. Now, in one human generation, observations point to a coherent shift in the pattern of temperature sensitive systems on all continents.

Already the increased frequency and intensity of extreme events referred to above has taken a toll in human lives, livelihood and property.

Many human systems are inherently sensitive to climate change. Examples in the IPCC report include:

- Changes in potential crop yields, especially reductions in most tropical and subtropical regions.
- Changes in water availability, especially losses in the sub-tropics.
- An increase in the number of people exposed to vector born diseases like malarial and water borne diseases like cholera.
- Increased losses of lives, livelihood, and property from heavy rains and sea level rise.

While a gradual increase in temperature might be accommodated by many natural and human systems, the projected increases in frequency, intensity, and persistence of extreme events has the potential to be enormously disruptive. Moreover the impacts of these changes will fall disproportionately on the poorest peoples. While this may be an obvious conclusion when comparing certain developed and developing countries, it will also be true within a developed country. The fraction of the population that is vulnerable to an extreme heat wave or flood will increase with the severity of the extreme event.

Many of the most devastating aspects of climate change will occur in tropical and subtropical regions, where 70% of the world's population live, many in developing countries. These are the regions that will be the most water stressed, suffer the greatest potential losses of agricultural capacity, and be most vulnerable to the expanded ranges of certain infectious diseases. Even allowing for possible benefits from climate change in some temperate regions, such as net gains in potential crop yields, the negative aspects of climate change in subtropical and tropical regions are likely to offset these positive aspect.

The following are evident in the recent IPCC assessment:

- Responses to climate change are already occurring in natural and human systems.
- It is highly likely that climate changes in the 21st century will be 2 - 10 faster than those of the 19th century.
- Increased frequency and severity of extreme events will be costly to natural and human systems.

Given the inertia in human system-climate system linkages, these findings lead inevitably to the conclusion that even the most optimistic scenarios for mitigating future climate change are unlikely to prevent significant damage from occurring. This is not to say that mitigation efforts such as a fully implemented Kyoto Protocol won't be effective; rather that their effect will not be evident for decades. Thus, an important finding of the IPCC is that adaptation will be absolutely necessary to minimize damage that is projected from future climate change. Natural systems will be affected in all regions from polar to tropical on all continents. Human systems will, however, be most vulnerable to climate change in Africa, Latin America, and Asia where adaptive capacity is low.

If we wish to avoid the loss of lives, livelihoods and property that will occur during our transition to a warmer world, it is imperative that we redouble efforts to both minimize the emissions of fossil fuel combustion products and prepare people and systems as best we can for the disruption that will ensue with the climate change that is now projected for the 21st century.

Suggested references and web sites

PDF versions of the IPCC WG I and II are available on http://www.usgcrp.gov/ipcc.

James J. McCarthy is Alexander Agassiz Professor of Biological Oceanography and Director of Harvard University's Museum of Comparative Zoology. He holds faculty appointments in the Department of Organismic and Evolutionary Biology and the Department of Earth and Planetary Sciences, and he is the Head Tutor for degrees in Environmental Science and Public Policy. He received his undergraduate degree in biology from Gonzaga University and his Ph.D. from Scripps Institution of Oceanography in La Jolla, California. His research interests relate to the regulation of plankton productivity in the sea, and in particular the cycling of nitrogen in planktonic ecosystems. He was the founding editor of the AGU Global Biogeochemical Cycles journal. He chaired the Scientific Committee of the International Geosphere Biosphere Programme from 1987 – 93. He is a member and past chair of ICSU's Advisory Committee on the Environment, and currently serves as Co-Chair of IPCC Third Assessment Report, WGII.

Email: jmccarthy@oeb.harvard.edu

Past and Future Changes in Climate Extremes

By David R. Easterling

Introduction

Observational and modeling studies into possible greenhouse induced climate change have traditionally focused on changes in mean and variance statistics (Easterling *et. al.* 1997, Groisman and Easterling 1994). However, recent events in many parts of the world have underscored the need to examine fluctuations and changes in extreme events. Although potential changes in long-term means are important from a number of standpoints, extreme events usually have the greatest and most immediate societal impact. Because of the high human and monetary costs often associated with extreme weather events many parts of society have become increasingly concerned about extreme events and their possible consequences. Some climate modeling studies involving enhanced greenhouse gases have suggested that if the climate changes over the next century, these changes will result in increases in extreme events, particularly increases in extreme temperature and precipitation events (Nicholls 1995, Karl and Knight 1998). In this paper, I provide a review of latest research on implications of global climate change on climate extremes based on analysis of observations and climate modeling.

Observed trends

It is clear from the observed records that there has been an increase in the global mean temperature of about 0.6°C since the start of the 20th century (Nicholls *et. al.*, 1996), and that this increase is associated with a stronger warming in daily minimum temperatures than maximums (Easterling *et. al.* 1997). Global precipitation has also increased over the same period (Nicholls *et. al.* 1996). Given these increases in mean values, what are now considered extreme events (e.g. a maximum daily temperature over 100F) are expected to become more common in the future (Mearns *et. al.* 1984). Therefore, it is useful to examine variability and trends in climate extremes and if there are indeed identifiable trends in these events, this would provide additional evidence that there is a discernable human impact on the climate.

Temperature extremes

Relatively little work has been completed related to changes in high frequency extreme temperature events such as heat waves, cold waves, and number of days exceeding various temperature thresholds. Easterling (2001) examined trends in the number of frost days in the U.S. and changes in the frost-free season length. Trends indicate that for the 1948-1999 period, there has been a slight decrease in the number of days below freezing, averaged over the entire U.S. and that the date of the last Spring freeze has gotten earlier, resulting in an increase in the frost-free season length. Two studies focused on the Northeastern U.S. support the notion that changes in the number of days exceeding certain temperature thresholds have occurred. Cooter and LeDuc (1995) showed that the start of the frost-free season in the Northeastern U.S. occurs 11 days earlier now than in the 1950s. In an analysis of 22 stations in the Northeastern U.S. for the 1948-1993 period, DeGaetano (1996) found significant trends to fewer extreme cold days and also trends to fewer warm maximum temperatures as well.

Apparent temperature, which combines temperature and humidity effects on the human body is another important measure, particularly for human health. Gaffen and Ross (1998) show regional summertime increases in days exceeding the 85th percentile threshold value for apparent temperature in the U.S.

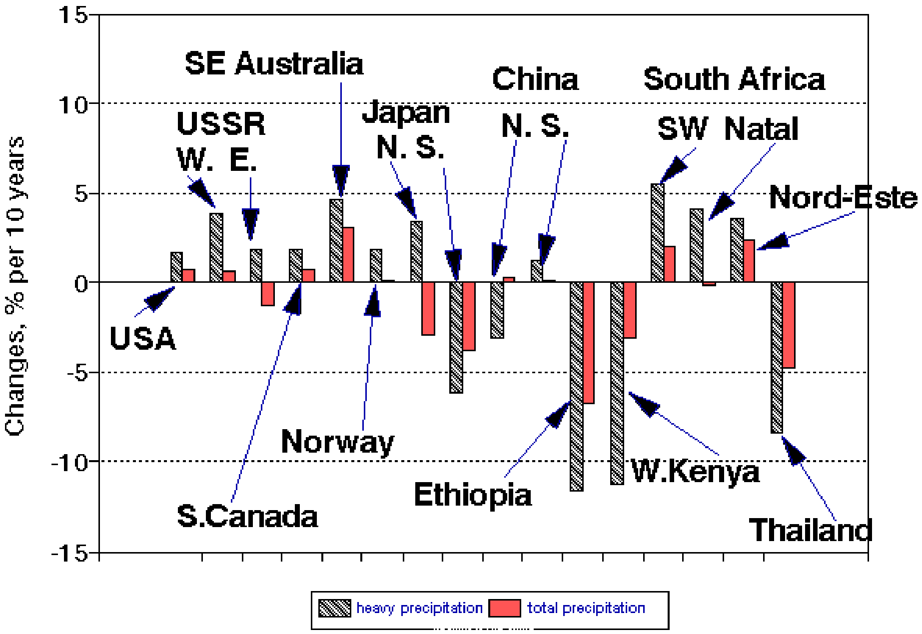
Short-duration episodes of extreme heat or cold are often responsible for the major impacts on health as shown by the 1995 heat wave in the Midwestern U.S. that resulted in hundreds of fatalities in the Chicago area (Changnon et. al. 1996). Although this heat wave was one of the worst short-duration events of the 20th Century (Kunkel *et. al.* 1996), an analysis of multi-day extreme heat episodes where the temperature exceeds the 10-year return period does not show any overall trend for the period of 1931-1997 (Kunkel *et. al.* 1999a). The most notable feature of the temporal distribution of these very extreme heat waves is the high frequency in the 1930s compared to the rest of the record. Again, this would appear at odds with the results of Gaffen and Ross (1998), however this points out the difficulty of comparing results using different periods, and different ways of defining an extreme event. Since Gaffen and Ross use apparent temperature, which includes humidity, part of their increase is likely due to increases in water vapor. Ross and Elliot (1996) show evidence of humidity increases over the U.S. for the 1971-1993 period. Extreme cold waves analyzed the same way also shows no overall U.S. trend since 1931 (Kunkel *et. al.* 1999a).

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

Analysis of heavy precipitation events in other parts of the world has shown that countries that experienced a significant increase (decrease) in precipitation over time have also experienced an increase (decrease) in heavy precipitation events (Easterling *et. al.* 2000). Figure 1 shows linear trends in both total annual precipitation, and heavy precipitation events for a number of countries around the world. This figure reinforces the point that, in general, when an increase in total annual rainfall is observed, more rainfall is falling in heavy daily events and vice versa. In addition, some countries that experienced no increase, or even a decrease in annual total precipitation during the 20th century, did observe an increase in heavy rainfall events suggesting that these countries are experiencing fewer days with rain, but more rainfall per day.

Figure 1. Linear trends in total seasonal precipitation and frequency of heavy precipitation events for various countries (adapted from Easterling et. al. 2000).



Drought and wet periods

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

While the analysis indicates no clear trend in occurrence of droughts, analysis of the areas of the U.S. experiencing excessive wetness appears to be increasing, particularly since the 1970s (Karl *et. al.* 1996). This is consistent with long-term increases in annual precipitation, and increases in heavy precipitation events discussed previously.

Tropical Storms

Overall, occurrences of Atlantic hurricanes do not show a statistically significant long-term trend over the 20th century however Landsea, *et. al.* (1999) have found a statistically significant decrease in intense hurricanes, those that cause the most damage. Furthermore, large variations of hurricane activity on interdecadal time-scales have been observed in this century (Gray *et. al.* 1997). From 1944 to the mid-1990s the number of intense and landfalling Atlantic hurricanes has declined.

Climate modeling results

Although recent improvements in climate models have resulted in improved ability of these models to simulate many aspects of climate, modelers still have a variety of problems to solve before regional climate conditions can be simulated accurately. However, recent analyses of climate model simulations for changes in extreme climate events are consistent with results from the observed record. For example, with increases in greenhouse gases, all models show warming of surface temperatures. With this warming comes a decrease in colder extremes, and increase in warmer extremes, with much of the warming occurring in minimum temperatures resulting in a decrease in the diurnal temperature range (Easterling *et. al.* 2000).

Analysis of changes in other extreme climate events includes

Table 1. Summary of analyses of different types of climate extremes, both those extremes based on climate statistics and event-driven extremes (see text for explanation).

	Observed (20th Century)	Modeling (end of 21st century)
Simple Extremes Based on Climate Statistics		
Higher Maximum Temperature	Very Likely	Very Likely
More Hot Summer Days	Likely	Very Likely
Increase in Heat Index	Likely	Very Likely
Higher Minimum Temperatures	Virtually Certain	Very Likely
Fewer Frost Days	Virtually Certain	Likely* (Higher minimum temperature)
More Heavy Multi-day Precipitation Events:	Likely	Very Likely (increased intensity of precipitation events)
More Heavy 1-day Precipitation Events	Likely	Very Likely (increased intensity of precipitation events)
Complex Event-Driven Climate Extremes		
More Heat Waves	Possible	Very Likely* (higher maximum temperatures)
Fewer Cold Waves	Very Likely	Very Likely* (higher minimum temperatures)
More Drought	Unlikely	Very Likely (reduced midlatitude summer soil moisture)
More Wet Spells	Likely	Likely (Increased precipitation at mid and high latitudes in winter)
More Tropical Storms	Unlikely	Possible
More Intense Tropical Storms	Unlikely	Possible
More Intense Mid-Latitude Storms	Possible	Possible
More Intense ENSO Events	Possible	Possible
More Common ENSO-like Conditions	Likely	Likely

* no direct model analyses, but these changes are physically plausible based on other simulated model changes; comparable changes simulated by the models are noted in parentheses.

The assessment of extremes here relies on very large scale changes that are physically plausible or representative of changes over many areas. There are some regions where the changes of certain extremes may not agree with the larger-scale changes. Therefore, the assessment here is a general one where observed and model changes appear to be representative and physically consistent with a majority of changes globally. Additionally, certain changes in observed extremes may not have been specifically itemized from model simulations, but are physically consistent with changes of related extremes in the future climate experiments and are denoted as such. The definitions of the uncertainty estimates for the possibility of changes in extremes differ between observations and models. For observations they are based on the following probability ranges: Virtually Certain > 99%, Very Likely 90-99%, Likely 67-90%, Possible 33-66%, Unlikely 10-33%, Very Unlikely 1-10%, Improbable <1%. For models they are based on the following degree of model agreement or physically plausibility: Virtually certain = many models have been analyzed for this change and all show it, Very Likely = a number of models that have been analyzed have shown such a change, or that change is physically plausible and can readily be shown for a larger group of models, Likely = some models that have been analyzed have shown such a change, or the change is physically plausible and could be shown for a larger group of models, Possible = only a few models have shown such a change, it is not physically obvious that such a change should occur, or the results from analyses from various models are mixed, Unlikely = some models that have been analyzed have shown that such a change specifically did not occur, or it is physically implausible and could be shown for a larger group of models, Very Unlikely = a number of models that have been analyzed have not shown such a change, or that change is physically implausible and could readily be shown for a larger group of models, Improbable = many models have been analyzed for this change and none show it. Note that changes in observations have already occurred, and the changes from models are projected to occur mainly due to increases in greenhouse gases. Thus where the observed changes agree with the models, they are qualitatively consistent with climate changes expected from increasing greenhouse gases (Source: Easterling *et. al.* 2000).

increases in heavy rainfall events with increases in overall annual precipitation totals (Zwiers and Kharin 1998). However, many recent model simulations for the 21st century find summer-time mid-continental drying, even with increased annual rainfall, due to enhanced evaporation and reduced summer-time rainfall (Weatherald and Manabe 1999).

With respect to other types of large-scale extremes, such as El Niño or La Niña (and the effects they have on weather around the world), or changes in mid-latitude and tropical storms, there is less agreement among various models. However, only recently has much confidence been placed on climate model abilities to simulate changes in these areas, and indeed some model experiments do show enhanced mid-latitude storms (Carnell and Senior 1998), tropical storms (Knutson *et. al.* 1998) or more persistent El Niño conditions (Timmerman *et. al.* 1999).

Analyses of different types of climate extremes: observations and modeling

Table 1 contains a summary of results of the analyses of extreme climate from both observations and modeling. Model results are summarized from recent (in the last 5 years) modeling experiments from numerous modeling groups as detailed in scientific journals. The table is divided into two kinds of extremes, those based on simple climate statistics such as number of days below freezing, and those defined as complex, event-driven events such as drought or flooding events. The table also gives a confidence factor in the language associated with each type of event. It is clear from this table that, at least qualitatively, there is consistency between what has been observed in the past and what is expected in the future under a greenhouse gas enhanced climate.

Summary and conclusions

There is still much work to be done in determining whether significant large-scale changes in these types of events are occurring in the U.S. and around the globe. One of the biggest problems in performing analyses of extreme climate events and if these changes are consistent with what should be expected in the future is the lack of established definitions for what constitutes an extreme. This lack of consensus and a lack of access to high-quality, long-term climate data for many parts of the world, with the time resolution appropriate for analyzing extreme events likely means it will be difficult to determine if extremes have changed, and how they may change in the future.

Acknowledgements. This article is a summary of the paper by Easterling et. al. (2000). David Easterling would like to acknowledge Dr. Gerald A. Meehl for his contributions to this paper.

Suggested references and Web sites

Carnell, R. E., and C.A. Senior, 1998 : Changes in mid-latitude variability due to greenhouse gases and sulphate aerosols, *Climate Dynamics*, 14, 369-383.

Changnon, S.A., K.E. Kunkel, and B. Reinke, 1996: Impacts and responses to the 1995 heat wave: A call to action., *Bulletin of the American Meteorological Society*, **77**, 1497-1506.

Cooter, E. and S. LeDuc, 1995: Recent frost date trends in the northeastern United States, *International Journal of Climatology*, **15**, 65-75.

Dai, A., K.E. Trenberth, and T.R. Karl, 1998: Global variations in droughts and wet spells., *Geophysical Research Letters.*, **25**, 3367-3370.

DeGaetano, A., 1996: Recent trends in maximum and minimum temperature threshold exceedences in the Northeastern United States, *Journal of Climate*, **9**, 1646-1657.

Easterling, D.R., B. Horton, P.D. Jones, T.C. Peterson, T.R. Karl, D.E. Parker, D.E., Salinger, M.J., Razuvayev, V., Plummer, N., Jamason, P., and C.K. Folland,1997:Maximum and minimum temperature trends for the globe, *Science,* **277**, 364-367.

Easterling, D.R., G.A. Meehl, C. Parmesan, S.A. Changnon, T.R. Karl, and L.O. Mearns, 2000: Climate extremes: Observations, modeling, and impacts, *Science*, **289**, 2068-2074.

Easterling, D.R., 2001: Recent changes in frost days and the frost-free season in the United States, submitted to, *Bulletin of American Meteorological Soc*iety.

Gaffen, D. and R. Ross, 1998: Increased summertime heat stress in the U.S., *Nature,* **396**, 529-530.

Gray, W.M., J. D. Scheaffer and C. W. Landsea, In *Hurricane: Climate and Socioeconomic Impacts.* H. F. Diaz and R. S. Pulwarty (Eds.), (1997).

Groisman, P.Y., and D.R. Easterling, 1994: Variability and trends of total precipitation and snowfall over the United States and Canada, *Journal of Climate* **7**, 184-205.

Groisman, P.Y., et. al., 1999: Changes in the probability of heavy precipitation: Important indicators of climatic change, *Climatic Change*, 42, 243-283.

Karl, T., R.W. Knight, D.R. Easterling, and R.G. Quayle, 1996: Indices of climate change for the

United States, *Bulletin of American Meteorological Society*, **77**, 279-291.

Karl, T.R. and R.W. Knight, 1998: Secular trends of precipitation amount, frequency, and intensity in the United States, *Bulletin of American Meteorological Society*, **79**, 1107-1119.

Knutson, T.R., R.E. Tuleya, and Y. Kurihara, 1998: Simulated increase of hurricane intensities in a CO2-warmed world, *Science*, **279**, 1018-1020.

Kunkel, K.E., S.A. Changnon, B.C. Reinke, and R.W. Arritt, 1996: The 1995 heat wave in the Midwest: A climatic perspective and critical weather factors, *Bulletin of American Meteorological Society*, **77**, 1507-1518.

Kunkel, K.E., R.A. Pielke, Jr., and S.A. Changnon, 1999a: Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of American Meteorological Society,* **80**, 1077-1098.

Kunkel, K.E., K. Andsager, and D.R. Easterling, 1999b: Long-term trends in extreme precipitation events over the conterminous United States, *Journal of Climate*, **12**, 2515-2527.

Landsea, C.W., R.A. Pielke, Jr., A.M. Mestas-Nunez, and J.A. Knaff, 1999: Atlantic basin hurricanes: Indices of climatic changes, *Climatic Change*, **42**, 89-129.

Mearns, L.O., R.W. Katz, and S.H. Schneider, 1984: Extreme high-temperature events: Changes in their probabilities with changes in mean temperature, *Journal of Applied Meteorology*, **23**, 1601-1613.

Nicholls, N., 1995: Long-term climate monitoring and extreme events, *Climate Change*, **31**, 231-245.

Nicholls, et. al., 1996: Observed Climate Variability and Change, in: *Climate Change 1995: The Science of Climate Change*, Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, 133 (1996)

Ross, R. J., and W. P. Elliott, 1996: Tropospheric water vapor climatology and trends over North America: 1973-1993, *Journal of Climate*, **9**, 3561-3574.

Timmerman, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif, and E. Roeckner, 1999: Increased El Niño frequency in a climate model forced by future greenhouse warming, *Nature*, **398**, 694-697.

Weatherald, R., and S. Manabe, 1999: Detectability of summer dryness caused by greenhouse warming., *Climatic Change*, **43**, 495-511.

Woodhouse, C., and J. Overpeck, 1998: 2000 years of drought variability in the central United States, *Bulletin of the American Meteorological Society*, **79**, 2693-2714.

Zwiers, F., and V.V. Kharin, 1998:Changes in the extremes of the climate simulated by CCC GCM2 under CO2 doubling, *Journal of Climate*, **11**, 2200-2222.

David R. Easterling is currently Principal Scientist at the National Climatic Data Center (NCDC) in Asheville, NC. Prior to joining NCDC in 1990, he served as an Assistant Professor in the Climate and Meteorology Program, Indiana University-Bloomington. He is a contributor to the Intergovernmental Panel on Climate Change (IPCC), and served with the National Assessment Synthesis Team, U.S. Global Change Research Program as a principal author on the report "The U.S. National Assessment: The Potential Consequences of Climate Variability and Change". His research interests include the detection of climate change in the observed record; the development of statistical methods for improving the quality of climate data; and the application of General Circulation Model simulations in developing climate change scenarios for use in assessing the potential effects of climate change. He received his Ph.D. from the University of North Carolina at Chapel Hill in 1987.

Email: David.Easterling@noaa.gov

How Should Precipitation Change as Climate Changes: Prospects for Increases in Extremes?

By Kevin E. Trenberth

How should precipitation change as the climate changes? This is a key question that could have a substantial impact on society and the natural environment, as it can directly affect availability of fresh water, the quality of potable water, and frequency and intensity of droughts and floods. Usually the only measure of precipitation cited is amount. But in addition to amounts we also need to be concerned with how often it rains or snows- the frequency - and the intensity or rate that it falls. By making these distinctions we can make more sensible statements about the likely precipitation changes as the climate changes and how to examine the data on precipitation.

The term "global warming" is often taken to refer to increases in global mean temperature accompanying the increases in greenhouse gases, such as carbon dioxide, in the atmosphere. In fact it should refer to the additional global heating - also referred to as radiative forcing - arising from the increased concentrations of greenhouse gases in the atmosphere, which produce an increase in downward infrared radiation. This increase in surface heating not only can increase surface temperatures but also can increase evaporation. In fact, it is more likely to do the latter as long as adequate moisture is available. For example, when the sun shines after a rainstorm, its heat dries up the puddles and the surface of the ground before it raises the surface temperature.

When the temperature increases, so does the water-holding capacity of the atmosphere. This is why we tend to use relative humidity as a measure of moisture as it signifies the percentage of moisture the atmosphere can hold rather than the absolute amount. In contrast, at very cold temperatures, the water-holding capacity of the atmosphere drops significantly (same properties are used in freeze drying process), and so the liquid water content of snow at temperatures below freezing is quite small.

Of course, enhanced evaporation depends on the availability of sufficient surface moisture. In fact surface moisture comes directly from evaporation as well as through transpiration in plants, together called evapotranspiration. However, it follows that naturally-occurring droughts are likely to be exacerbated by enhanced potential evapotranspiration (drying).

The combination of increased water carrying capacity of the atmosphere and enhanced evapotranspiration means that the actual atmospheric moisture should increase. In fact, global observations of atmospheric humidity confirm this to be happening in many places around the world. For example, observations indicate that over the United States and Gulf of Mexico, moisture amounts in the lowest 20,000 feet of the atmosphere increased about 10% from 1973 to 1993.

Furthermore, globally there must be an increase in precipitation to balance the enhanced evaporation but the processes by which precipitation is altered locally are not well understood. Precipitating systems of all kinds (e.g., rain clouds, thunderstorms, extratropical cyclones, hurricanes, etc.) feed mostly on the moisture already in the atmosphere at the time the system develops. Precipitation then occurs through convergence of available moisture on the scale of the system. Hence, the atmospheric moisture content directly affects rainfall and snowfall rates.

Therefore, it is argued that global warming leads to increased moisture content of the atmosphere, which in turn favors stronger rainfall events, thus increasing risk of flooding. In other words, according to this theory, when it rains it should rain harder than it used to with similar storms twenty or thirty years ago, when there was less moisture in the atmosphere. Observations confirm that this is the case in many parts of the world, e.g., in the United States, Japan and Australia. It is further argued that one reason why increases in rainfall amount should be spotty is because of mismatches in the rates of rainfall versus evaporation. Evaporation occurs typically at about 0.2 inches per day but moderate or heavy rain can easily be an inch or more per day. Thus rain dries out the atmosphere and the weather system runs out of moisture, unless the winds bring in more moisture from remote areas.

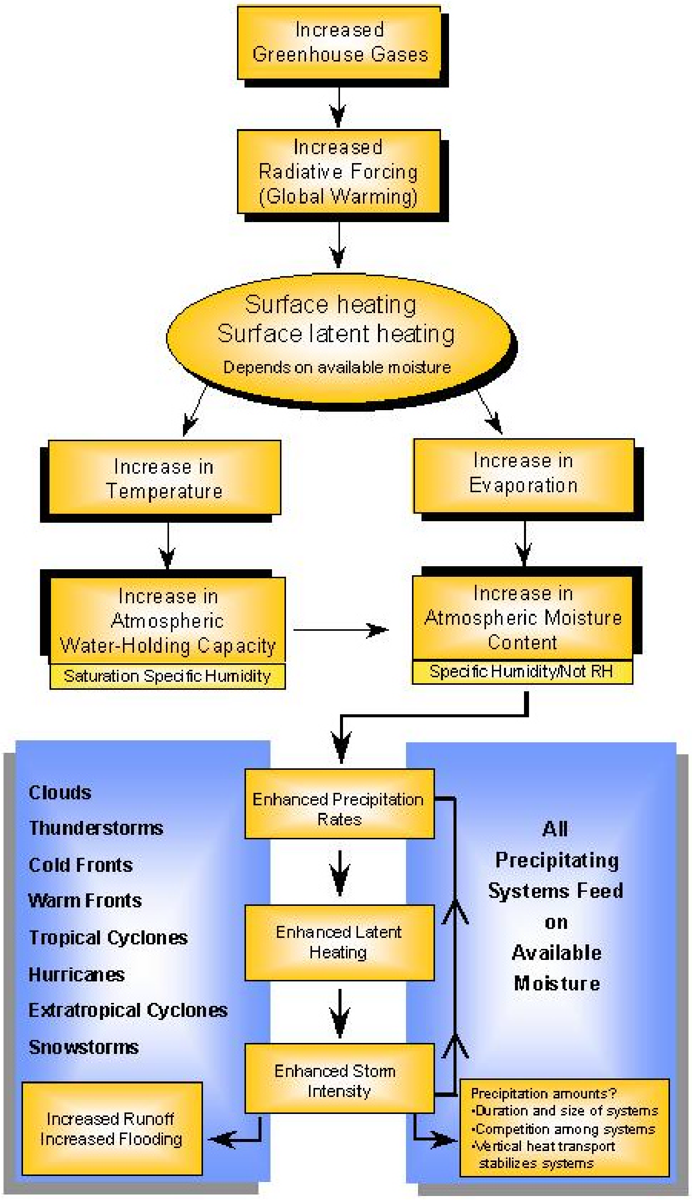
The arguments on how climate change can influence moisture content of the atmosphere, and its sources and sinks are schematically shown in Figure 1. The sequence provided here is simplified by omitting some of the feedbacks that come into play. For example, an increase in atmospheric moisture may lead to increases in relative humidity and increased clouds, which could cut down on solar radiation and reduce the energy available at the surface for evaporation. These feedbacks are included in the climate models and alter the magnitude of the surface heat available for evaporation in different models but not its sign. Figure 1 provides the rationale for why precipitation rates and frequencies as well as accumulations are important in understanding what is going on with precipitation locally. The accumulations depend greatly on the frequency, size and duration of individual storms, as well as the intensity, and these depend on atmospheric static stability (which relates to the vertical temperature structure of the atmosphere and whether it favors or suppresses perturbations) and other factors as well. In particular, the need to vertically transport heat absorbed at the surface is a factor in convection and extratropical weather systems, both of which act to stabilize the atmosphere. Increased greenhouse gases also stabilize the atmosphere. Those are additional considerations in interpreting model responses to increased greenhouse gas simulations.

However, because of constraints in the surface energy budget, there are also implications for the frequency and/or efficiency of precipitation. The global increase in evaporation is determined by the increase in surface heating and these control the global increase in precipitation. Moisture amounts are not limited by this but instead are limited by the moisture carrying capacity, and so precipitation intensities are apt to increase more rapidly than amounts, implying that the frequency of precipitation must decrease, raising the likelihood of fewer but more intense events.

Hence it is argued that increased moisture content of the atmosphere favors stronger rainfall and snowfall events, thus increasing risk of flooding. Although there is a pattern of heavier rainfalls observed in many parts of the world, another factor in whether it actually floods and causes damage is increasing settlement of flood plains which changes vulnerability to flooding. Also, flooding records are confounded by changes in land use, construction of culverts and dams, and other means designed to control flooding.

The above arguments suggest that there is not such a clear expectation on how local total precipitation amounts should change, except as an overall global average.

Figure 1. Schematic outline of the sequence of processes involved in climate change and how they alter moisture content of the atmosphere, evaporation, and precipitation rates. All precipitating systems feed on the available moisture leading to increases in precipitation rates and feedbacks (source: Trenberth 1998).



With higher average temperatures in winter expected, more precipitation is likely to fall in the form of rain rather than snow, which will increase both soil moisture and run off. In addition, faster snowmelt in spring is likely to aggravate springtime flooding. In other places, complicated patterns of precipitation change should occur where storm tracks shift. Where the storms previously tracked gets drier and where they shift becomes wetter. Beyond this, it is suggested that examining moisture content, rainfall rates and frequency of precipitation and how they change with climate change may be more important and fruitful than just examining precipitation amounts in understanding what is happening, both in the real world and in climate models. But many data analyses are not done to illuminate these aspects. To be compatible with life times of significant rain events, yet still deal with whole storms rather than individual rain cells, examination of hourly precipitation data is recommended. Such data are also retrievable from climate models.

Suggested references and Web sites:

- For references on observations of moisture content of the atmosphere in different regions of the world and changes in precipitation patterns see:

Iwashima, T., and R. Yamamoto, 1993: A Statistical Analysis Of The Extreme Events: Long-Term Trend Of Heavy Daily Precipitation, *Journal of Meteorological Society of Japan*, **71**, 637-640.

Karl, T. R., and R. W. Knight, 1998: Secular Trends Of Precipitation Amount, Frequency And Intensity In The USA, *Bulletin of American Meteorological Society,* **79**, 231-242.

Kunkel, K. E., K. Andsager and D. R. Easterling, 1999: Long-Term Trends In Extreme Precipitation Events Over The Conterminous United States And Canada, *Journal of Clim*ate, **12**, 2515-2527.

Ross, R. J., and W. P. Elliot, 1996: Tropospheric Water Vapor Climatology And Trends Over North America: 1973-93*, Journal of Clim*ate, **9**, 3561-3574.

Suppiah, R., and K. J. Hennessy, 1998: Trends In The Intensity And Frequency Of Heavy Rainfall In Tropical Australia And Links With The Southern Oscillation, *Australian Meteorological Mag*azine, **45**, 1-17.

- For more information on how changes in atmospheric moisture content affects rainfall and snowfall see:

Trenberth, K. E., 1998: Atmospheric Moisture Residence Times And Cycling: Implications For Rainfall Rates With Climate Change, *Climate Change*, **39**, 667-694.

Trenberth, K. E., 1999: Conceptual Framework for Changes of Extremes of the Hydrological Cycle with Climate Change, Climatic *Change*, **42**, 327-339.

- For general information on Global Climate Change see:

IPCC Third Assessment: working Groups I and II Reports, 2001 can be obtained at http://www.usgcrp.gov/ipcc.

IPCC (Intergovernmental Panel of Climate Change), 1996. *Climate Change 1995: The Science of Climate Change*. Eds. J. T. Houghton, F. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Cambridge Univ. Press, Cambridge, U.K., 572pp.

Dr. Kevin E. Trenberth is Head of the Climate Analysis Section at the National Center for Atmospheric Research. He was a convening lead author of the 1995 IPCC Scientific Assessment of Climate Change and he was Co-chair of the Scientific Steering Group for the World Climate Research Programme's Climate Variability and Predictability (CLIVAR) program from 1996-1999. He is a fellow of the American Meteorological Society and American Association for Advancement of Science, and an honorary fellow of the Royal Society of New Zealand.

Email: trenbert@ucar.edu

Implication of Global Warming for Public Health

By Paul R. Epstein

Adapted from "Is Global Warming Harmful to Health," by Paul R. Epstein.

Introduction

Today, few scientists doubt the atmosphere is warming. Most also agree that the rate of heating is accelerating and that the consequences of the temperature change will become increasingly disruptive. As glaciers melt, sea levels will rise, inundating settlements along many low-lying coasts; meanwhile, the regions suitable for farming will shift, and extreme weather will strike harder and more often.

Yet, less-familiar effects could prove equally disruptive. Notably, sophisticated computer models predict that global warming, and other climate alterations it induces, will expand the incidence and distribution of many serious medical disorders. Disturbingly, these forecasts seem to be coming true. Heating of the atmosphere can influence health through several routes. In this paper, I will address the worrisome health effects of global warming and disrupted climate patterns.

Mosquitoes rule in the heat

Diseases transmitted by mosquitoes-such as malaria, dengue fever, yellow fever and several kinds of encephalitis-are among those eliciting the greatest concern as the world warms. Mosquitoes acquire disease-causing microorganisms when they draw a blood meal from an infected animal or person. Then the pathogen reproduces inside the insects, which may deliver disease-causing doses to the next individuals they bite.

Mosquito-borne disorders may become increasingly prevalent because the insect carriers, or "vectors," are highly sensitive to meteorological conditions. Cold weather limits mosquitoes to seasons and regions where temperatures stay above certain minimums. Winter freezing kills many eggs, larvae and adults outright and the adults will not reproduce or fly in the cold. Anopheles mosquitoes, which transmit malaria parasites (such as Plasmodium falciparum), cause disease only where temperatures routinely exceed 60 degrees F. Similarly, Aedes aegypti, responsible for transmitting yellow fever and dengue fever, conveys virus only when temperatures rarely fall below 50 degrees F.

Excessive heat kills the insects as effectively as the cold does. Nevertheless, within their survivable range of temperatures, mosquitoes proliferate faster and bite more, as the air becomes warmer. At the same time, greater heat speeds the rate at which pathogens inside them reproduce and mature. At 68 degrees F, the immature malaria parasite takes 26 days to develop fully, but at 77 degrees F, it takes only 13 days. The Anopheles mosquitoes that spread the parasite live only several weeks; warmer temperatures up the odds that the parasites will mature in time for the mosquitoes to transfer the infection. As whole areas heat up, then, mosquitoes can expand into formerly forbidden territories, bringing illness with them. Further, warmer winter and nighttime temperatures will enable them to cause more disease, and for longer periods, in the areas they already inhabit.

The extra heat is not the only factor in encouraging a rise in mosquito-borne diseases. Intensifying droughts and floods accompanying global warming can each help to trigger outbreaks by creating breeding grounds for many of the insects, which lay their eggs in still water. As floods recede, they leave puddles. In times of drought, rivers and streams can become stagnant pools, and people may put out containers to catch water; these pools and pots, too, can become incubators for new mosquitoes. And the insects can gain another boost if climate changes or other processes (such as alterations of habitats by humans) reduce the populations of predator species that normally keep mosquitoes numbers in check.

Mosquitoes on the march

Malaria and dengue fever are two of the mosquito-borne diseases likely to spread as global temperatures rise. Malaria (marked by fever, chills, aches and anemia), already affects some 300 million people and takes the lives of more than a million each year. Some models project that by the end of the 21st century ongoing warming could enlarge the zone of potential malaria transmission from an area containing 45 percent of the world's population to an area containing about 60 percent. Other models project smaller changes. But all the models may underestimate the potential, as they are based on average temperatures. Warming is occurring twice as fast as average warming during the winter and the fastest winter-warming is occurring near the poles. That news is bad indeed, considering that no vaccine is available and that the causative parasite is becoming resistant to standard drugs.

True to the models, malaria has begun to extend its range northward and southward from its base in the tropics. The U.S. has long been home to anopheles mosquitoes and Malaria. The disease circulated here decades ago. By the 1980s, mosquito-control programs and other public health measures had restricted locally transmitted malaria to California. In the 1990s, however, the hottest decade of the century, outbreaks of locally transmitted malaria have occurred during hot spells in Texas, Georgia, Michigan, New Jersey, New York and Toronto. These episodes undoubtedly originated with people who contracted the illness in the tropics and probably are not due to heating alone. But the parasites clearly found friendly conditions in the U.S.-enough warmth and humidity, and plenty of mosquitoes able to convey them from one victim to another. Malaria has returned to South Korea, parts of southern Europe, the former Soviet Union and to coastal South Africa (along the Indian Ocean).

Dengue or "breakbone" fever (a severe flulike viral illness that sometimes causes fatal internal bleeding) is spreading, as well. Today it afflicts an estimated 50 million to 100 million in the tropics and subtropics (mainly in urban areas and their surroundings). It broadened its range enormously in the Americas over the past 10 years and reached down to Buenos Aires by the end of 1990s. It has also found its way to northern Australia and the vector was reported in New Zealand in February 2001. Neither a vaccine nor a specific drug treatment is yet available.

Although these expansions of malaria and dengue or their vectors certainly fit the predictions, the cause of that growth cannot be conclusively traced to global warming. Other factors could have been involved as well-such as disruption of the environment in ways that favor mosquito proliferation, declines in mosquito-control and other public health programs, and rises in drug and pesticide resistance.

The case for a climatic contribution becomes stronger, however, when other predicted consequences of global warming appear in concert with disease outbreaks. Such is the case in the highlands around the world. There, as predicted, warmth is climbing up many mountains, along with plants and butterflies; and summit glaciers in the Andes are melting at a rate 32 times the rate just three decades ago. Since 1970, the height at which temperatures are below freezing all year round has ascended almost 500 feet in the tropics. Marching upward, too, are mosquitoes and mosquito-born diseases.

In the 19th century, European colonists in Africa settled in the cooler mountains to escape the dangerous, swamp air ("mal aria") that fostered disease in the lowlands. Today, many of those havens are compromised. Insects and insect-borne diseases are being reported at high elevations in South and Central America, Asia and east and central Africa. Malaria is circulating in highland urban centers, such as Nairobi, Kenya, and in rural highlands, such as Papua New Guinea. In the 1990s, Ae. aegypti mosquitoes, which were once limited by temperature to about .6 miles in elevation, were found at 1 mile in highlands of northern India and at 1.3 miles in the Colombian Andes. Their presence magnifies the risk that dengue and yellow fever could follow. Dengue itself has appeared beyond the mile mark in Taxco, Mexico.

Patterns of insect migration change faster in the mountains than they do at sea level. Those alterations can thus serve as indicators of climate change and of diseases likely to expand their range.

Opportunists like sequential extremes

The increased climate variability accompanying warming will probably be more important as the rising heat itself altering the ecosystems upon which we depend and in fueling unwelcome outbreaks for certain vector-borne illnesses. For instance, warm winters followed by hot, dry summers (a pattern that may become all too familiar as the atmosphere heats up), is known to favor transmission of Saint Louis encephalitis and other infections that cycle among birds, urban mosquitoes and humans.

This sequence seems to have abetted the surprise emergence of the West Nile virus in New York City last year. No one knows how this virus found its way into the U.S. But one reasonable explanation for its amplification centers around the weather's effects on Culex pipiens mosquitoes, which accounted for the bulk of the spread. These urban dwellers typically lay their eggs in damp basements, catch basins, sewers and dirty ponds.

The interaction between the weather, the mosquitoes and the virus probably went something like this: The mild winter of 1998–99 enabled many of the mosquitoes to survive into the spring, which arrived early. Drought in spring and summer concentrated nourishing organic matter in their breeding areas and simultaneously killed off mosquito predators, such as darning needles and dragonflies, that would otherwise have helped limit mosquito populations. Drought would also have led birds to congregate more, as they shared fewer and smaller watering holes, many of which were frequented, naturally, by mosquitoes.

Once mosquitoes acquired the virus, the heat wave that accompanied the drought would speed up viral maturation inside the insects. Consequently, as infected mosquitoes sought blood meals, they spread the virus to birds at a rapid clip. As bird after bird became infected, so did more mosquitoes, which ultimately fanned out to infect human beings. Torrential rains toward the end of August provided new puddles for the breeding of other mosquitoes, unleashing an added crop of potential virus carriers.

Like mosquitoes, other disease-conveying vectors tend to be "pests"-opportunists that reproduce quickly and thrive under disturbed conditions that would harm other species. Climate variability in the 1990s also contributed to the appearance in humans of new rodent-borne ailment: the hantavirus pulmonary syndrome (a highly lethal, hemorrhage-causing disease). In mice the condition spreads through the air from animal to animal. The infection can be transmitted to humans when people inhale viral particles hiding in the excretions of rodents. The sequential weather extremes that set the stage for the first human eruption, in the U.S. Southwest in 1993, were prolonged drought interrupted by intense rains.

First, a drought that persisted in the region from 1987 to 1992 may have reduced the pool of animals that prey on rodents-raptors (owls, eagles, prairie falcons, red-tailed hawks and kestrals), coyotes and snakes. Then droughts yielded to heavy rains in December 1992 and January 1993, giving the rodents a bounty of food, in the form of grasshoppers and piñon nuts, and swelling their ranks. This population explosion enabled a virus that was either isolated in a small population or was inactive to spread to many rodents, including ones that brought the disease to their human neighbors. By the end of summer 1993, predators had returned, mice populations fell and the outbreak had abated.

Subsequent episodes of hantavirus pulmonary syndrome in the U.S. have been limited, in part because early-warning systems now indicate when rodent-control efforts have to be stepped up and because people have learned to be more careful about avoiding the animals' droppings. But the disease has appeared in Latin America, where some ominous evidence suggests that it may be passed from one person to another.

As the natural ending of the first hantavirus episode demonstrates, ecosystems can usually survive occasional extremes. They are even strengthened by seasonal changes in weather conditions, because the species that live in changeable climates have to evolve an ability to cope with a broad range of conditions. But long-lasting extremes and very wide fluctuations in weather can overwhelm ecosystem resilience. (Persistent ocean heating, for instance, is menacing coral reef systems, and drought-driven forest fires are threatening forest habitats.) And ecosystem upheaval is one of the most profound ways in which climate change can affect human health. Pest control is one of nature's under appreciated services to people; well-functioning ecosystems that include diverse species help to keep nuisance organisms in check. If increased warming and weather extremes result in more ecosystem disturbance, that disruption may foster the growth of opportunist populations and enhance the spread of disease.

Unhealthy water

Beyond exacerbating the vector-borne illnesses mentioned above, global warming would probably elevate the incidence of waterborne diseases, including cholera (a cause of severe diarrhea). Warming itself can contribute to the change, as can a heightened frequency and extent of droughts and floods. It may seem strange that droughts would favor waterborne disease, but they can wipe out supplies of safe drinking water and concentrate contaminants that might otherwise remain dilute. Further, the lack of clean water during a drought interferes with good hygiene and safe rehydration of those who have lost large amounts of water because of diarrhea or fever.

Floods favor waterborne illnesses in different ways. They wash sewage and other sources of pathogens (such as Cryptosporidium) into supplies of drinking water. They also flush fertilizer into water supplies.

Fertilizer and sewage can each combine with warmed water to trigger expansive blooms of harmful algae. Some of these blooms are directly toxic to humans who inhale their vapors; others contaminate fish and shellfish, which, when eaten, sicken the consumers. Recent discoveries have revealed that algal blooms can threaten human health in yet another way. As they grow bigger, they support the proliferation of various pathogens, among them Vibrio cholerae, the causative agent of cholera.

Drenching rains brought by a warmed Indian Ocean to the Horn of Africa in 1997 and 1998 offer an example of how people will be affected as global warming spawns added flooding. The downpours set off epidemics of cholera as well as two mosquito-borne infections: malaria and Rift Valley fever (a flulike disease that can be lethal to livestock and people alike).

To the west, Hurricane Mitch stalled over Central America in October 1998 for three days. Fueled by a heated Caribbean, the storm unleashed torrents that killed at least 11,000 people. But that was only the beginning of its havoc. In the aftermath, Honduras reported thousands of cases of cholera, malaria and dengue fever. Beginning in February of 2000, unprecedented rains and a series of cyclones inundated large parts of southern Africa. Floods returned to Mozambique in 2001. The floods in 2000 in Mozambique and Madagascar killed hundreds, displaced thousands and spread both cholera and malaria. Such events can also greatly retard economic development, and its accompanying public health benefits, in affected areas for years.

Solutions

The health toll taken by global warming will depend to a large extent on the steps taken to prepare for the dangers. The ideal defensive strategy would have multiple components.

One would include improved surveillance systems that would promptly spot the emergence or resurgence of infectious diseases or the vectors that carry them. Discovery could quickly trigger measures to control vector proliferation without harming the environment, to advise the public about self-protection, to provide vaccines (when available) for at-risk populations and to deliver prompt treatments.

In the spring of 2000, efforts to limit the West Nile virus in the northeastern U.S. followed this model. On seeing that the virus had survived the winter, public health officials warned people to clear their yards of receptacles that can hold stagnant water favorable to mosquito breeding. They also introduced fish that eat mosquito larvae into catch basins and put larvicide pellets into sewers.

Sadly, however, comprehensive surveillance plans are not yet realistic in much of the world. And even when vaccines or effective treatments exist, many regions have no means of obtaining and distributing them. Providing these preventive measures and treatments should be a global priority.

A second component would focus on predicting when climatological and other environmental conditions could become conducive to disease outbreaks, so that the risks could be minimized. If climate models indicate that floods are likely in a given region, officials might stock shelters with extra supplies. Or if satellite images and sampling of coastal waters indicate that algal blooms related to cholera outbreaks are beginning, officials could warn people to filter contaminated water and advise medical facilities to arrange for additional staff, beds and treatment supplies.

Research reported in 1999 illustrates the benefits of satellite monitoring. It showed that satellite images detecting heated water in two specific ocean regions and lush vegetation in the Horn of Africa could predict outbreaks of Rift Valley fever in the Horn five months in advance. If such assessments led to vaccination campaigns in animals, they could potentially forestall epidemics in both livestock and people.

A third component of the strategy would attack global warming itself. Human activities that contribute to the heating or that exacerbate its effects must be limited. Little doubt remains that burning fossil fuels for energy is playing a significant role in global warming, by spewing carbon dioxide and other heat-absorbing, or "greenhouse," gases into the air. Cleaner energy sources must be put to use quickly and broadly, both in the energy-guzzling industrial world and in developing nations, which cannot be expected to cut back on their energy use. (Providing sanitation, housing, food, refrigeration and indoor fires for cooking takes energy, as do the pumping and purification of water and the desalination of seawater for irrigation. Solar and wind power for such activities would improve conditions and help mitigate climate change. In parallel, forests and wetlands need to be restored, to absorb carbon dioxide, maintain animal biodiversity and filter floodwaters and contaminants before they reach water supplies.

The world's leaders, if they are wise, will make it their business to find a way to invest in these solutions. Climate, ecological systems and society can all recoup after stress, but only if they are not exposed to prolonged challenge or to one disruption after another. The Intergovernmental Panel on Climate Change, established by the United Nations, calculates that halting the ongoing rise in atmospheric concentrations of greenhouse gases will require a whopping 60 to 70 percent reduction in emissions.

I worry that effective corrective measures will not be instituted soon enough. Climate does not necessarily change gradually. The multiple factors that are now destabilizing the global climate system - greenhouse gases, land-use changes and loss of stratospheric ozone -- could cause it to jump abruptly out of its current state. At any time, the world could suddenly become much hotter or even much colder. Such a sudden, catastrophic change is the ultimate health risk—one that must be avoided at all costs.

Suggested references and Web sites

- For more information on Global climate change see:

http://www.ipcc.ch/

http://www.ipcc.ch/pub/reports.htm

- For more information on implications of global climate change on public health see:

Richard Levins, T. Auerbuch, U. Brinkmann, I. Eckardt, P. R. Epstein, T. Ford, N. Makhoul, C. dePossas, C. Puccia, A. Spielman and M. E. Wilson, 1994: The Emergence of New Disease, *American Scientist*, **82**, No. 1, 52–60.

Climate Change and Human Health, 1996: Edited by A. J. McMichael, A. Haines, R. Slooff and S. Kovats. World Health Organization, World Meteorological Organization, United Nations Environmental Program.

The Regional Impacts of Climate Change 1997: An Assessment of Vulnerability, 1997: Edited by R. T. Watson, M. C. Zinyowera and R. H. Moss. Cambridge University Press, 1997. Summary from the Intergovernmental Panel on Climate Change available at: http://www.ipcc.ch/pub/reports.htm

Epstein, P. R., H. F. Diaz, S. Elias, G. Grabherr, N. E. Graham, W. J. M. Martens, E. Mosley-Thompson and J. Susskind, 1998: Biological and Physical Signs of Climate Change: Focus on Mosquito-Borne Diseases, *Bulletin of the American Meteorological Society*, **79**, 409–417.

Dr. Paul R. Epstein, an M.D. trained in tropical public health, is associate director of the Center for Health and the Global Environment at Harvard Medical School. He has served in medical, teaching and research capacities in Africa, Asia and Latin America and has worked with the Intergovernmental Panel on Climate Change, the National Oceanic and Atmospheric Administration, and the National Aeronautics and Space Administration to assess the health effects of climate change and to develop health applications for climate forecasting and remote-sensing technologies.

Email: paul_epstein@hms.harvard.edu

Upcoming Events

18th Conference on Weather Analysis and Prediction, 14th Conference on NWP, and 9th Conference on Mesoscale Processes
30 July – 2 August 2001 Ft. Lauderdale, FL.
www.ametsoc.org

82nd American Meteorological Society Annual Meeting
13 – 18 January, 2002, Orlando, FL.
www.ametsoc.org

The Climate Report
Volume 2, Number 1
Winter 2001

Publisher
The Climate Report is a quarterly publication of Climate Risk Solutions, Inc.
233 Harvard Street, Suite 307
Brookline, MA 02446 USA

Editor Maryam Golnaraghi

Contributing Editor
A Hossein Farman-Farmaian

Production Intoto, Inc.

Subscriptions
Tel: 617.566.0077
Fax: 617.566.1144
E-mail: info@climaterisksolutions.com