Environment Canada   Environnement Canada

Extreme Weather and Climate Change

by

David Francis
Lanark House Communications
Toronto

and

Henry Hengeveld
Atmospheric Environment Service
Environment Canada

This document contributes to state of the environment reporting

This paper contains a minimum of 50% recycled fibres,
including 10% post-consumer fibres.

INTRODUCTORY COMMENTS AND ACKNOWLEDGEMENTS

Extreme Weather and Climate Change *was prepared in response to questions often posed by policy makers and the general public about whether or not perceived changes in weather behaviour in recent years, particularly with respect to extreme weather events and related disasters, are real, and, if so, whether such changes are linked to climate change. It is being published as the second in a series of "special"* Climate Change Digest *reports aimed at explaining and assessing our current understanding (or lack thereof) of some of the more complex and controversial aspects of climate change science. This series complements the regular CCD series focused on scientific studies relating to impacts of climate change.*

This report was prepared by David Francis of Lanark House Communications (Toronto), in collaboration with Henry Hengeveld, Senior Science Advisor on Climate Change with the Atmospheric Environment Service of Environment Canada.

The authors wish to acknowledge with appreciation the valuable input, through review and critique, of the following individuals: Bill Hogg, Doug Whelpdale, and Francis Zwiers (AES Climate Research Branch); Pam Kertland, David Phillips, and John Stone (AES Policy, Program and International Affairs Directorate); David Etkin and Roger Street (AES Environmental Adaptation Research Group); Eric Taylor (Environment Canada's Pacific and Yukon Region); Jim Abraham and Paul Galbraith (Environment Canada's Atlantic Region); and Heather Johannesen (Halifax).

The French text of this report (available separately) was translated by Marie-France Guéraud of the Translation Bureau, Public Works and Government Services (Montreal) and was edited by Gilles Tardif of Enviroedit (Keswick, Ontario). Graphic design, artwork, and technical production were provided by BTT Communications (Toronto).

Photo credits: Canadian Press (pages 7 and 16); Environment Canada, Ontario Region (page 24); Water Resources Branch, Manitoba Department of Natural Resources (page 25).

Copies of this publication may be obtained, free of charge, by writing to:

Climate and Water Products Division
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario
M3H 5T4

(416) 739-4328

Published by Authority of the Minister of the Environment

Cataloque No. En57-27/1998-01E
ISBN 0-662-26849-0
ISSN 0835-3980

TABLE OF CONTENTS

Extreme Weather and Climate Change

Is the world's weather becoming more extreme? So far, during the 1990s alone, the world has witnessed at least half a dozen floods of epic proportions in Canada and the United States, central Europe, and southern China as well as intense droughts in northern China, northern Vietnam, North Korea, and southern Europe. In 1993, the northeast coast of the United States received its biggest snowstorm in more than a century. At the end of 1996, it was the turn of Victoria, which was paralyzed by the biggest snowfall in its recorded weather history. Then, in January 1998, Canada's worst-ever ice storm left the Montreal area and eastern Ontario without power for weeks. Western Europe, usually noted for the moderation of its climate, was pounded by four major storms in the winter of 1990. In 1987, southern England was hit by its worst storm since 1705. In 1995, heat waves killed more than 500 people in northern and central India and more than 550 in Chicago, numbers that pale in comparison, however, to the estimated 5,000–10,000 heat-related deaths that occurred in the central and eastern U.S. in the summer of 1980.

Hurricanes, floods, droughts, and other extreme weather events have the potential to cause death and destruction on a catastrophic scale. If they become more common, the costs to society will increase enormously.

The sheer number of such events within the past two decades raises some serious questions about the current and future state of the global climate. Are these events part of a long-term trend towards more extreme weather, or are they just a temporary aberration? Are they the result of purely natural forces? Or could they be linked in some way to climate change caused by the buildup of greenhouse gases in the atmosphere? The answers to these questions are vitally important. Hurricanes, floods, droughts, and other extreme weather events have the potential to cause death and destruction on a catastrophic scale. If they become more common, the costs to society will increase enormously. If these extremes are an inevitable consequence of greenhouse warming, then our current estimates of the impacts of climate change, serious as they are, will have been far too optimistic, and the need to make decisive cuts in greenhouse gas emissions will become even more pressing, as will the need to undertake increasingly expensive adaptive measures.

Is Extreme Weather Becoming More Common?

The number of extraordinarily severe floods, storms, and other weather calamities that have occurred within the past 15 to 20 years would seem to suggest that such events are becoming more common. Figures compiled by the world insurance industry, for example, show a dramatic increase in losses from weather-related disasters in recent decades. For all of the 1960s insured losses from windstorms amounted to $2.0 billion (in 1990 U.S. dollars) worldwide. By the 1980s that figure had crept up to $3.4 billion for the decade. In just the first three years of the 1990s, however, it leapt to $20.2 billion. Before 1987 a billion-dollar insurance loss from climate events was rare, but between January 1988 and January 1997 there were 23 such events in the United States alone. Canada has not yet had a billion dollar insurance loss from a weather disaster, although total costs (including insured and non-insured losses) for a few events, such as the 1996 Saguenay flood and the 1998 eastern ice storm, have exceeded this amount.

These figures certainly suggest a major rise in the number of destructive weather events, but cost alone is not necessarily an accurate indicator of climate

WHAT IS EXTREME WEATHER?

Extreme weather, in the most obvious sense, is weather that lies outside a locale's normal range of weather intensity. It is therefore, by definition, infrequent or rare. Extreme weather is also potentially destructive, although not all extreme weather events end in disasters.

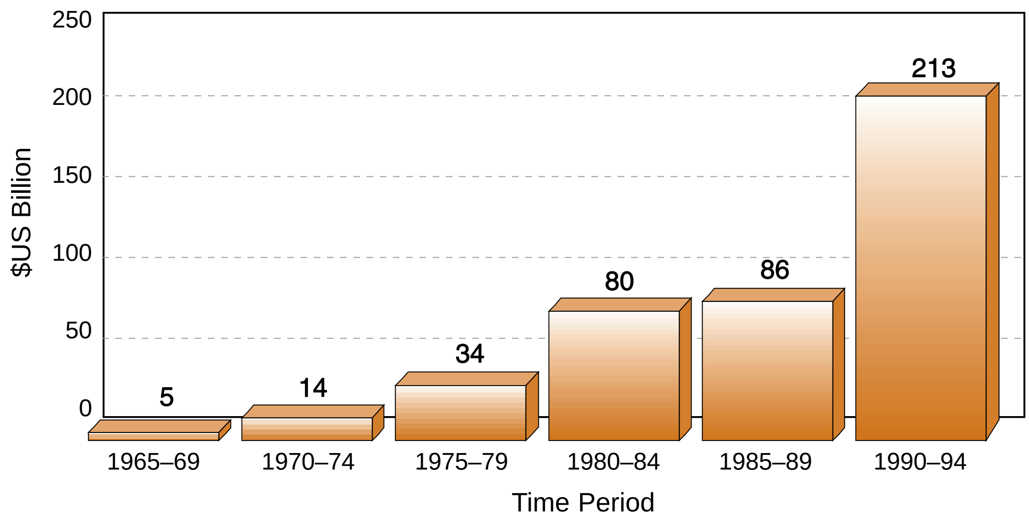
For some weather events, the idea of what constitutes an extreme can vary from place to place. It often depends on what a region is used to experiencing and what it is prepared for. A 20-cm snowfall would be an extreme event for Washington, D.C., for example, but not for Montreal. In Washington such an event would come close to an emergency. In Montreal it would be merely an inconvenience.

Extreme events such as hurricanes, tornadoes, and ice storms often require the presence of a number of special circumstances before they can take place. Many extreme events also come about as a result of a combination of factors, such as the merging of two weather systems or the occurrence of a severe weather event in tandem with some other factor that intensifies its impact. Hurricane Hazel, for example, was a weakening tropical storm when it merged with a deep low pressure system northwest of Toronto in October 1954, producing torrential rains and the deadliest flood in Canadian history. In the case of the Saguenay flood, water levels in the Saguenay basin were already at unusually high levels when the largest rainstorm in the region's recorded weather history struck on July 19, 1996. Some flooding would still have occurred if water levels had been normal, but the results might not have been as catastrophic.

trends. As well as being influenced by the number and severity of such events, costs also reflect the size and wealth of the population affected by them, and these numbers have been increasing as well. Two American researchers, Roger Pielke, Jr. and Christopher Landsea, for example, have suggested that increased damage costs from hurricanes in the U.S. can be attributed to three factors: inflation, population growth in vulnerable coastal areas, and the increasing prosperity of the people affected. When these factors are taken into account, they argue, the economic impact of hurricanes in the U.S. has actually declined in recent decades.

Apply the same kind of analysis to world losses from natural disasters as a whole, however, and the results are quite different. Data from Munich Re, one of the world's largest re-insurance firms, show that direct economic losses (in 1992 U.S. dollars) from natural disasters worldwide increased by a factor of 43 between the last half of the 1960s and the first half of the 1990s. Global wealth (as measured by GDP), on the other hand, increased by a factor of 2.5 and population by 25%. That means that, with inflation already adjusted for by the use of constant dollars, economic growth and population increase account for less than a fourfold rise in these losses. Other

ECONOMIC LOSSES FROM NATURAL CATASTROPHES, 1965–1994



Source: Adapted from Munich Re (1996)

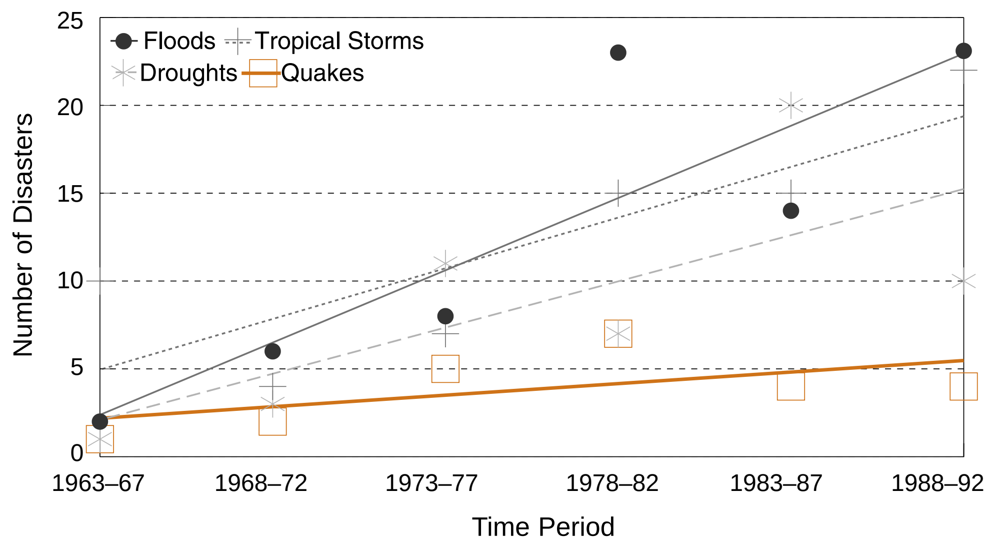
Dramatic increases in economic losses from natural catastrophes, most of them weather-related, imply an increase in weather extremes. These trends must be interpreted cautiously, however, since they are also heavily influenced by population increases and economic growth.

population factors, such as migration to vulnerable areas, might well account for further losses, but it is unlikely that they could explain all of the remaining increase. Since by far the largest part of the increase in these losses was due to weather-related events, an increase in severe weather is a possibility that has to be looked at seriously.

The likelihood that weather-related disasters are on the rise is also supported by an analysis done by the Geneva Secretariat for the International Decade for Natural Disaster Reduction. It looked at the rates of change for the four largest categories of major natural disasters – floods, tropical storms, droughts, and earthquakes. Between the mid-1960s and the early 1990s the number of all of these disasters increased, but the weather-related disasters increased at a much higher rate. To qualify as a major disaster, an event had either to cause damage equal to at least 1% of the affected country's gross domestic product, to affect more than 1% of the country's population, or to cause more than 100 deaths. These criteria partially filter out distortions arising from population and economic growth but not totally. Nevertheless, since trends for both earthquakes and weather disasters would be affected more or less equally by these factors, there is some reason to believe that the data reflect an actual increase in severe weather events.

However, insurance losses and disaster trends are at best an indirect barometer of climate change. Historical climate records should provide much more direct evidence of change, but teasing out trends and probabilities for rarely occurring weather extremes in a body of highly variable data is a tricky proposition. Problems with data quality and irregularities, especially in older records that provide the benchmark for change, make it even more difficult. Add in the fact that relatively little statistical analysis has been directed specifically towards extreme events, and it is

Rate of increase of natural disasters (floods, tropical storms, drought, and earthquakes), 1963–1967 to 1998–1992



Source: Adapted from McCulloch and Etkin (1993)

Data compiled by the Geneva Secretariat of the International Decade for Natural Disaster Reduction show increases in all of the four leading natural disaster categories over the past three decades. Weather-related categories, however, show the highest rate of increase. Since trends for all categories are likely to be more or less equally affected by social and economic factors, there is reason to believe that the data reflect an actual increase in severe weather events.

not surprising that the climate record is still far from shedding as much light as it could on trends in weather extremes.

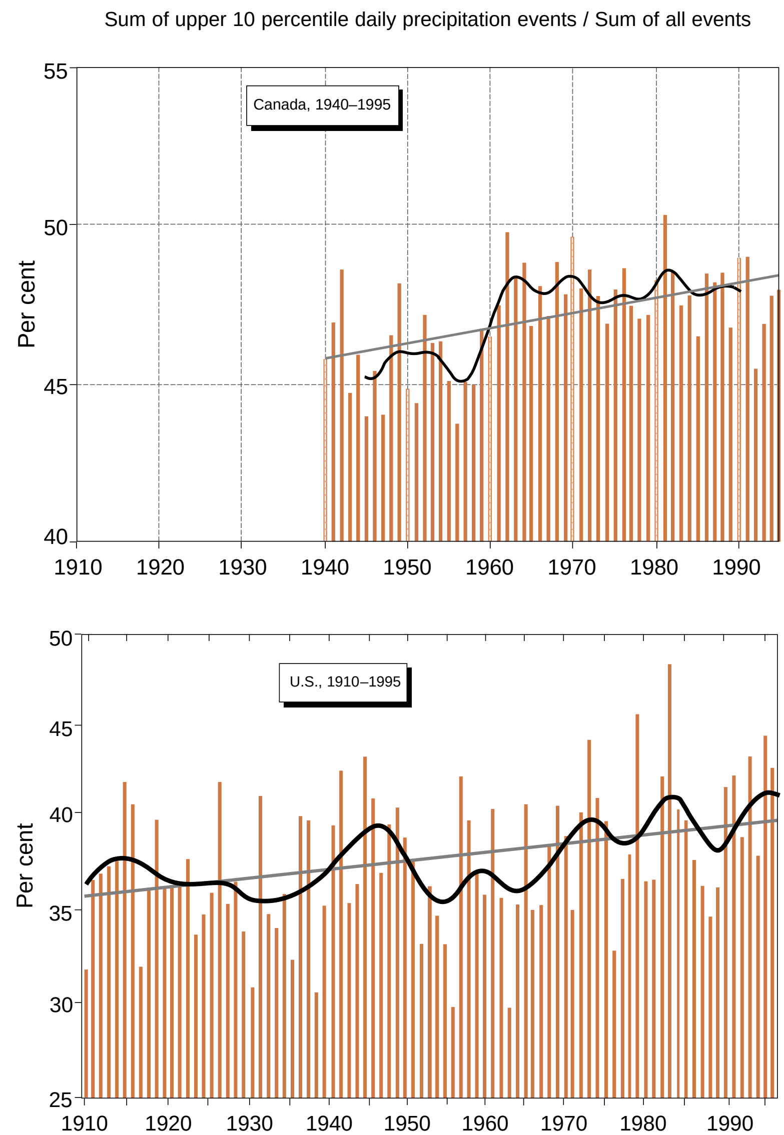
Nevertheless, work completed in the last few years has shown the emergence of some significant regional trends, although no consistent pattern of change in weather extremes is yet apparent globally. The most reliable trends are those for temperature and precipitation (not surprisingly, since these are the most widely measured climate variables). Many parts of the world have shown a decrease in the occurrence of low temperature extremes, as would be expected in a warming climate. Surprisingly, though, there has not yet been a noticeable increase in high temperature extremes. The reason appears to be related to the tendency in many regions for winter temperatures to have increased more than summer temperatures and for overnight lows to have warmed more than daytime highs.

Temperature, therefore, has actually shown a lessening of extremes, at least so far, but a tendency towards more extreme precipitation is apparent across much of the land area of the Northern Hemisphere. Heavy rainfalls have increased in Japan, the United States, the former Soviet Union, China, and countries around the North Atlantic rim. Canadian records also reveal a trend towards heavier precipitation since 1940, although the increase has been mainly confined to the North.

Drought, on the other hand, has become more common since the 1970s in parts of Africa as well

Extreme precipitation trends in Canada and the United States

In both Canada and the United States, the percentage of annual precipitation coming from the heaviest 10% of the year's precipitation events has increased during the second half of the century. Canadian trends, however, have been heavily influenced by precipitation increases in the North. In southern Canada, extreme precipitation events have actually declined over the course of the century.



Source: Environment Canada

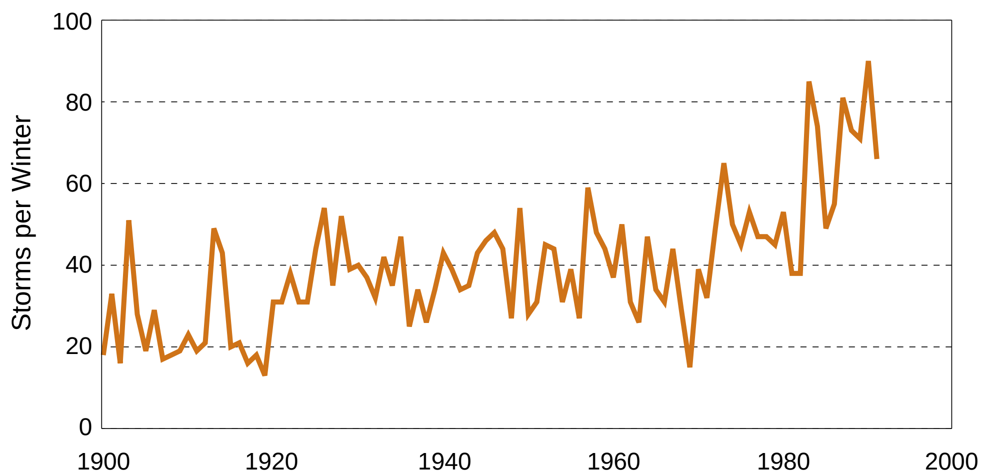
as along the coasts of Chile and Peru and in north-eastern Australia. The North American prairies also saw an increase in drought during the 1980s, although these years were not as dry as either the 1930s or the 1950s.

Severe storms would also appear to be on the increase in some regions since the mid-1980s, but the statistical evidence is mixed. Canadian researcher Steven Lambert recently examined winter storm activity in the extratropical Atlantic and Pacific since the beginning of the present century. Using intense low pressure systems as a marker for unusually severe storms, he saw little change in the number of these storms before 1970. After 1970, however, severe winter storms became considerably more frequent, particularly in the Pacific. Other researchers using similar methods to analyze storms in the North Atlantic have also noted an increase in storm activity. In addition, a study of storms along the eastern coast of North America found an increase since the mid-1970s, although storms in this area were still not as frequent as they had been before 1965. What was different about the post-1965 storms though was their destructiveness. Seven of the region's eight most destructive storms of the past half century had occurred within the last 25 years.

Other researchers have questioned these conclusions. The quality of the weather records on which they have been based, they argue, is too uneven. Instead, they have preferred using a statistical technique known as downscaling, which estimates local conditions on the basis of relationships with larger-scale weather patterns. Applied to weather data for the eastern North Atlantic, the method has shown no statistically significant trend in recent storm behaviour for the region.

Thunderstorms are another important category, because they are frequently associated not only with high winds and intense rainfalls but also with hail and tornadoes. Thunderstorm activity is difficult to measure on a broad scale, however, because thunderstorms are highly localized and brief in duration. Consequently, they are unlikely to be recorded unless they occur near a weather station. Still, there is evidence that thunderstorms have become more frequent in some areas. In the United States, for

Frequency of winter storms in the Northern Hemisphere



Source: Adapted from Lambert (1996)

This graph, from an analysis of severe winter storms in the extratropical Atlantic and Pacific by Steven Lambert of Environment Canada, shows a striking increase in storm activity after 1970. Other studies of extratropical storms, however, have given varied results. Some are consistent with Lambert's findings, while others have not found a statistically significant trend in storm frequency.

The Edmonton tornado of July 31, 1987, left 27 dead and 200 injured and caused more than $250 million in property damage. It has been shown that the monthly frequency of tornadoes in the Prairie Provinces corresponds closely to the average monthly temperature. This suggests that warmer spring and summer months could bring an increase in tornado activity to the region.

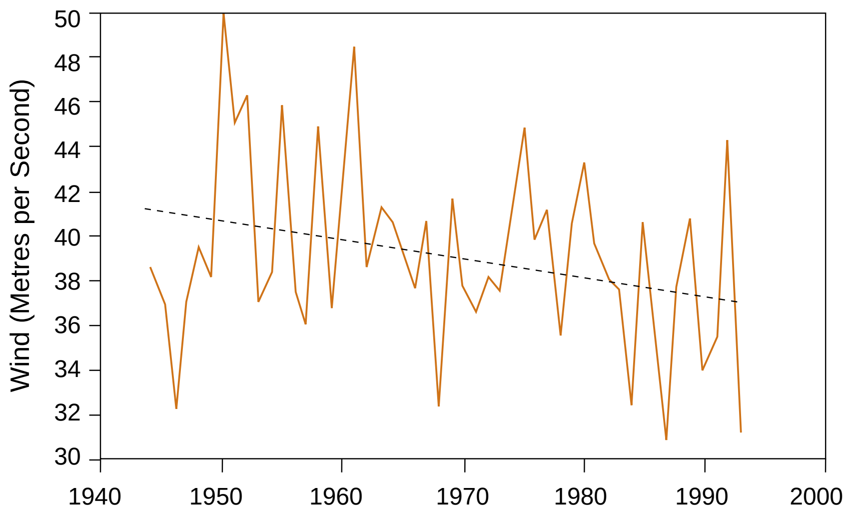
example, the fact that most of the increase in heavy rainfall has occurred during the summer suggests an increase in the number of severe thunderstorms. Other evidence comes from northern Australia, where there has also been an increase in heavy rainfalls during the summer, and France, where severe hail falls have become more common during the summer months. Analysis of cloud patterns also suggests a general increase in thunderstorm activity in the tropical regions of the world.

Tornadoes are even more difficult to measure than thunderstorms, since they are usually very short-lived and do not always occur in populated areas where they are certain to be observed. In the United States, where tornadoes occur more frequently than anywhere else, studies have shown no increase in the occurrence of strong tornadoes, although reports of less severe tornadoes have increased. When Environment Canada researcher David Etkin looked at tornado activity on the Canadian prairies, however, he found that tornadoes were more frequent in warm springs and summers. As warm springs and summers would become more common as a result of climate change, his results imply an eventual increase in tornado frequency on the Prairies if seasonal temperatures rise beyond present normal values.

Hurricanes are the most destructive storms, but earlier records of these are often incomplete. Until the advent of satellites, storms that did not touch land in populated areas often went unrecorded. Records for the tropical Atlantic have been reasonably good since 1970, however, and these, interestingly enough, show a declining trend in annual hurricane frequency, although both 1995 and 1996 saw a larger than average number of storms. Annual average maximum wind speeds of Atlantic hurricanes have also decreased for much of the past half century, though there has been no trend in the highest wind speeds of individual storms from year to year. Hurricane activity in the Pacific, on the other hand, appears to have increased, but the data are not as reliable as for the Atlantic.

In addition to looking for trends in individual weather phenomena, climate researchers are also beginning to develop tools that will indicate a tendency towards extremes across a spectrum of weather events. The advantage of this approach is that it provides a more direct answer to the question

Average annual maximum sustained wind speed of Atlantic hurricanes, 1940–1993



Source: Adapted from Landsea et al. *(1996)*

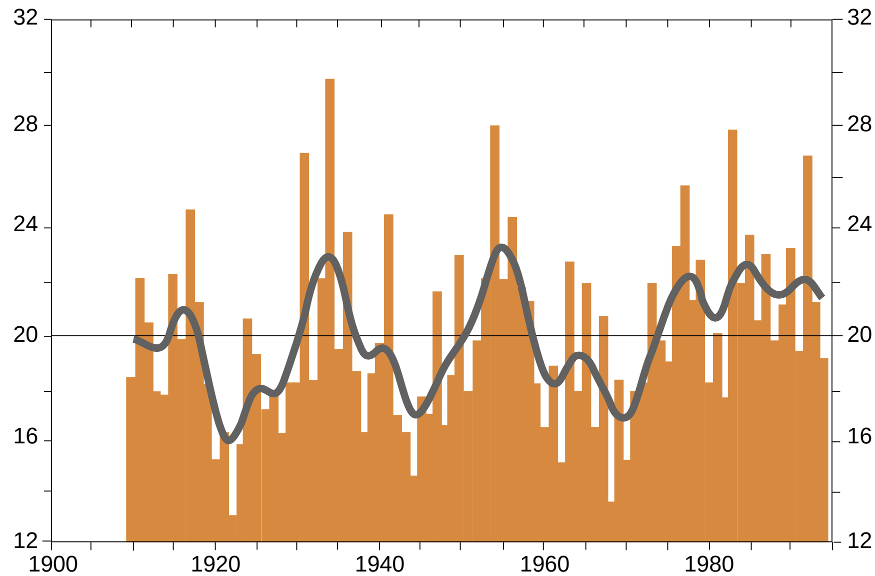
Average maximum wind speeds of Atlantic hurricanes have generally decreased over the past 50 years. The number of Atlantic hurricanes has also declined over the same period. The number of hurricanes in the Pacific, however, may have increased.

of whether the climate in general is becoming more extreme. The Climate Extremes Index of the U.S. National Climate Data Center provides an interesting illustration of this approach. It combines several measures of the area covered by extreme temperatures and precipitation, drought, and soil moisture surpluses into a single value representing the relative predominance of extreme weather events in a given year. Beginning in 1910, it shows an almost cyclical waxing and waning of extreme events, with pronounced peaks for the mid-1930s and mid-1950s when the human influence on the climate was much less than it is today. The index rises to peak levels again in the mid-1970s, but this time it no longer subsides to the same extent as it did previously. In fact, it remains above the average through the 1980s and 1990s. The transformation of the peak into a plateau could indicate that more severe weather conditions are becoming a permanent part of the American climate at least, but since similar indices are not as yet available for other countries and regions, it is impossible to say whether this represents a broader hemispheric or global trend.

Overall, then, the weather record is inconclusive, though occasionally suggestive. The world could be in the early phases of a fundamental shift towards a climate in which extremes of many kinds are more prevalent. Or the present cluster of extreme events could be a temporary phenomenon. To what extent either of these explanations is correct depends very much on what has caused extreme events to occur so often within the past 15 to 20 years.

There are three possible causes to consider. First, if the clustering of extremes proves to be temporary, it could be explained entirely as the result of the natural variability of the climate system. The peaks on the graph of the U.S. Climate Extremes Index in the 1930s and 1950s, for example, illustrate what is likely a natural surge in the frequency of extreme weather.

The U.S. Climate Extremes Index



Source: U.S. National Climate Data Center

The U.S. Climate Extremes Index combines a variety of measures of temperature and precipitation extremes to give a single annual measure of the frequency of extreme events. Although it does not track all types of extremes – tornadoes, for example, are not included – it does provide a useful approximation of trends in weather extremes on a regional scale. The index shows pronounced but brief peaks in the 1930s and 1950s and a more sustained period of severe weather activity since the mid-1970s.

If, however, the climate is undergoing a fundamental shift in which extremes become more common, then we must look for some basic change in the forces acting on the climate system. That raises two additional possibilities. The change could be the result of an entirely natural process, such as an increase in solar radiation, or it could be a consequence of human actions, most notably the enhancement of the greenhouse effect.

Natural Variability

Variability is a natural feature of the climate system. It may appear as short-term fluctuations that come and go within the span of a decade or longer-term changes that last for a century or more. Such variations are the net result of a number of factors. One of these is simply the random variability that occurs within a complex, quasi-chaotic system such as the climate system because of the almost infinite number of forces acting on it. Still, there are clear theoretical limits to this variability, and these are set by large-scale controls and feedback processes that govern the amount of energy entering and leaving the atmosphere. These include such factors as the intensity of the sun's radiation, the earth's orbit and the tilt of its axis, and the concentration of greenhouse gases in the earth's atmosphere. How the system behaves within the limits set by these controls, however, is much harder to determine. In the case of extreme events, this unpredictability can often be much greater because the worst extremes are frequently the result of a chance combination of less extreme events, such as a storm and a high tide or the merging of two storm systems.

Some short-term climatic abnormalities have a more identifiable physical basis. Large volcanic eruptions can exert a powerful cooling effect on weather in many parts of the world. This happens because sulphur particles shot into the stratosphere by the eruption can partially block incoming sunlight for a number of years. During the summer of 1816, for example, there were repeated frosts in Quebec and the New England states. These have been linked to the extremely powerful eruption of Mt. Tambora in Indonesia in 1815. More recently, the eruption of Mt. Pinatubo in the Philippines in the summer of 1991 – the most powerful eruption of the twentieth century – brought cooler temperatures to much of the rest of the world during the next two years. It is estimated that Pinatubo reduced the earth's average surface temperature in 1992 by somewhere between 0.3°C and 0.5°C. In Canada, the Pinatubo cooling was most evident in Ontario and Quebec that year, and the Great Lakes–St. Lawrence region recorded its coolest July since the 1880s.

Short-term fluctuations may also be the result of more systematic variations within the climate system. The severity of winters in western Europe, for example, tends to follow the ups and downs of the North Atlantic Oscillation, an alternation in pressure differences between Iceland and the Azores. In years when the difference is large, western Europe enjoys milder winters, while western Greenland and Labrador experience unusually cold weather. When the difference is small, the situation is reversed. The North Atlantic Oscillation tends to switch phase every couple of years, although it may occasionally get stuck in one phase for up to a decade or more. It also appears to follow a longer cycle in which it is predominantly in one phase for 30–40 years and then predominantly in the other for the next 30–40 years. From 1900 until the late 1940s, the positive phase, in which pressure differences are large, predominated. From then until around 1980, the negative phase was more common. Since then, the oscillation has returned to its positive phase. The cause of the oscillation is not well understood, but it is clearly a natural phenomenon which affects the severity of winter weather in different parts of the North Atlantic region.

A somewhat similar but much better known phenomenon is the El Niño, the periodic warming of surface waters in the eastern half of the equatorial Pacific. It usually lasts from 12 to 18 months and occurs once every two to ten years. Because the warming occurs in tandem with the Southern Oscillation (a reversal of pressure patterns over the South Pacific), climatologists commonly refer to it as the El Niño Southern Oscillation or ENSO.

Normally the equatorial Pacific is swept by strong easterly trade winds, which cause warm surface waters to pile up on the western side of the Pacific and bring colder, deeper water to the surface on the eastern side. In an El Niño year, the trade winds slacken and the warm water accumulated in the west gradually returns to the eastern Pacific, preventing the cooler water from reaching the surface. Consequently, the surface temperature of the eastern Pacific begins to rise, changing the pattern of rising and falling air masses over the entire equatorial Pacific and ultimately altering the atmospheric circulation over much of the rest of the world.

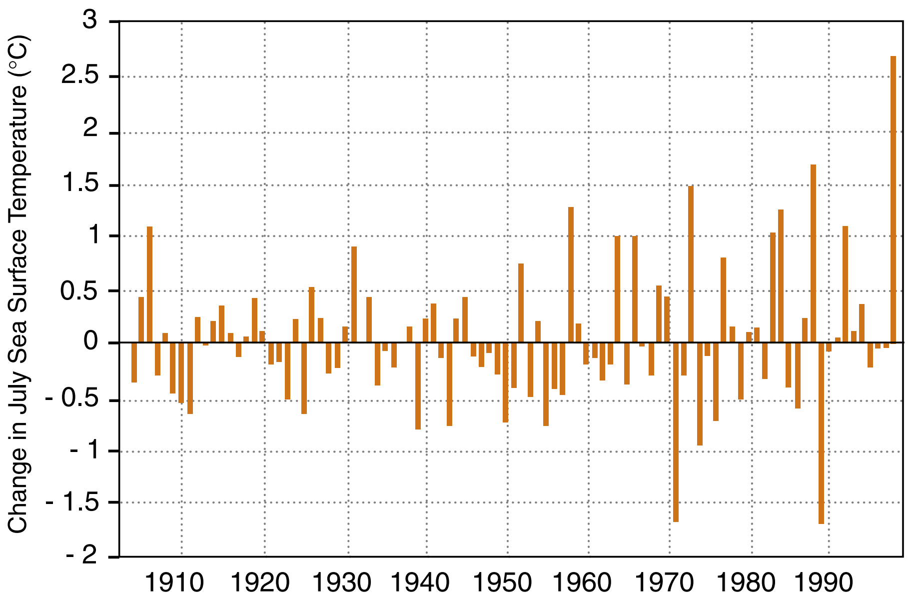
By distorting atmospheric circulation patterns, ENSOs bring profound changes to customary weather patterns in the tropics and even in the middle latitudes. Droughts in Australia and Africa, floods in Brazil and Paraguay, freak snowstorms in the Middle East, and poor monsoon rains in India and Indonesia have at various times been linked to ENSO conditions. In Canada, the effects of ENSOs vary considerably, but the most common result is an unusually warm and somewhat drier winter in most parts of the country except the Atlantic provinces and the high Arctic.

Since the mid-1970s, El Niños have been both more frequent and more persistent. This change in ENSO behaviour can account, at least in part, for many of the weather anomalies of the past couple of decades. Some of the increase in the global average temperature of the past two decades, for example, can be linked to ENSO events, as can precipitation declines in North Africa, Southeast Asia, Indonesia, western Central America, and other parts of the tropics and sub-tropics. Hurricane patterns are also affected by the ENSO cycle, because changes to the upper air flow in the tropics in El Niño years tend to suppress hurricane formation in the Atlantic and enhance it in the southeast Pacific. The decline in the frequency of Atlantic hurricanes since 1970 and the apparent increase in Pacific hurricanes may well reflect this relationship. However, the recent intensification of El Niño activity itself raises serious questions. It has no precedent in the climate records of the past 120 years and, according to some climate researchers, no precedent within the past 1000 years. Why has it happened now? Is it a natural occurrence, or is it a response to human interference with the climate system?

Some short-term climatic fluctuations may also be related to minor changes in the intensity of the sun's radiation that accompany the sunspot cycle. The number of sunspots on the sun's surface increases and then decreases over a cycle that varies from 7.5 to 16 years and averages slightly more than 11 years. Sunspots tend to appear in polarized pairs, and over a double cycle of about 22 years, on average, the polarity of the pair will reverse. Although sunspots are actually cooler than the surrounding solar surface, they are associated with hotter areas known as faculae. Consequently an increase in the number of sunspots indicates an increase in radiation from the sun. The change in the sun's energy output over a single cycle, however, is quite small. Recent estimates place it at about 0.1%.

Many climate records show pronounced cycles that, for a time at least, parallel either the single or the

El Niño frequency and intensity in the 20th century



Source: James P. Bruce

The occurrence of El Niños is marked by an abnormal warming of the eastern equatorial Pacific. As the graph for July sea surface temperature shows, major warming events (in which the sea surface temperature is 1°C or more warmer than the 1950–1980 average) have not only been more frequent in the second half of the century but have also involved a greater degree of warming. A strengthening of the opposing La Niña phenomenon (related to abnormal cooling of the sea surface) is also evident in the second half of the century.

EL NIÑOS AND CLIMATE CHANGE

What is the driving force behind El Niños? According to a theory proposed by De-Zheng Sun, a researcher with the U.S. National Oceanographic and Atmospheric Administration, it's the temperature difference between the tropical ocean surface and the ocean depths.

Sun's findings are based on experiments with a model of the ocean-atmosphere system in which the temperature of the deep ocean was held steady while the ocean surface was warmed by solar heat and a gradually increasing greenhouse effect. As the ocean surface became warmer, a temperature difference between the eastern and western sides of the model's ocean began to develop. At 29.2°C an ENSO-like oscillation of ocean temperatures set in and increased in magnitude as the temperature of the ocean surface was increased. The oscillations, which go through a complete cycle in four years, closely resemble the behaviour of the tropical Pacific Ocean. The experiment also showed that the oscillations would not occur in a narrower basin, such as that of the Atlantic.

If Sun's theory is correct, then El Niños would initially become stronger in a warming climate because the surface ocean would warm faster than the deep ocean. Over time, however, the intensity of El Niños would probably moderate as the deep ocean gradually became warmer and the temperature difference between it and the surface diminished. Nevertheless, it would take several hundred years for this process to take place.

double sunspot cycles. Major droughts in the U.S. midwest, for example, have tended to occur at roughly 20-year intervals. However, attempts to link major climatic patterns to the sunspot cycle usually run into difficulty when they attempt to explain how such small changes in solar output could cause relatively large climatic fluctuations. One of the more plausible mechanisms suggested so far links sunspot peaks to warming in the lower stratosphere, which then affects circulation patterns in the rest of the atmosphere below. Although the warming still amounts to only a fraction of a degree, climate model studies by Joanna Haigh of the University of London suggest that such small variations in stratospheric temperature might be enough to shift winter storm tracks in Europe northward from the Mediterranean by an average of about 700 km.

Some or all of these mechanisms could account for a temporary increase in weather extremes. The longer the extremes persist, however, the less adequate these explanations become and the more we must consider the possibility of a long-term shift in climate behaviour. An enhanced greenhouse effect is one possible reason for such a shift, but climate can also change dramatically over the longer term for purely natural reasons.

The great ice age glaciations of the past 2 million years are the most spectacular examples of such changes, but smaller variations over periods of a few hundred to a few thousand years have also occurred during our present postglacial climate. The best-known example of these variations is the event known as the Little Ice Age. During this period, which lasted from about 1400 to 1850, the climate in Europe and many other parts of the world cooled noticeably. By the mid-1600s, when the cooling reached its maximum extent, the earth's average surface temperature had dipped to nearly 1°C below its present value. The Little Ice Age and other variations in global temperatures during the past 10,000 years are thought to be due primarily to changes in the output of energy from the sun, though other factors may also have played a role. The central part of the Little Ice Age, for example, coincided with a period of minimal sunspot activity between 1645 and 1715 known as the Maunder Minimum. During that time, the output of solar energy is estimated to have been somewhere between 0.1% and 0.7% lower than it is today.

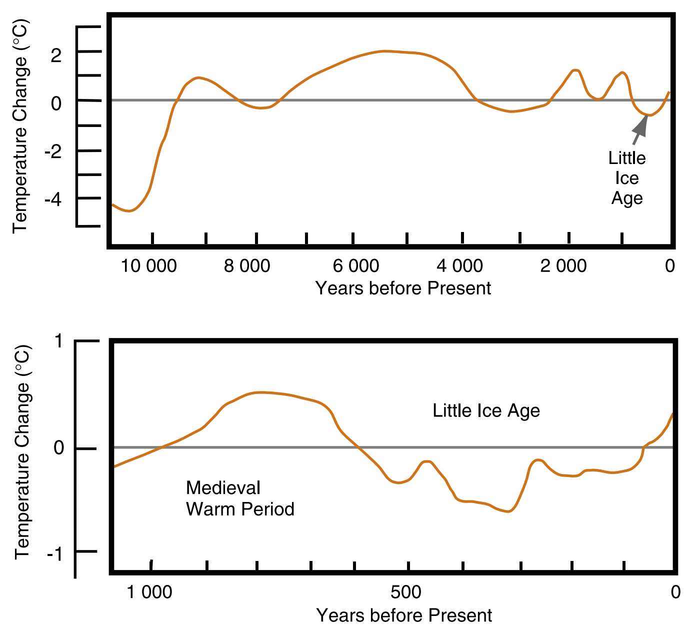
The sun's output has been increasing since about 1850, and recent scientific estimates attribute about half of the warming of the past century and a third of that since 1970 to this increase. There is growing evidence, however, that the enhanced greenhouse effect is largely responsible for the rest of the warming influence on our present climate. If the surge in extreme weather events is the result of a fundamental, long-term shift in climate, then it is greenhouse warming rather than a change in solar output that is more likely to be driving the change.

Greenhouse Warming and Weather Extremes

Why would greenhouse warming cause an increase in weather extremes? One reason is that the additional warming will change the distribution of heat and thus the flow of energy through the climate system. This will in turn alter the circulation patterns of the atmosphere and the oceans, and it will also modify the hydrological cycle by which water is circulated between the earth's surface and the air. As a result, the position of many of the world's major storm tracks could shift significantly. To see what the effects of such a shift might be, one has only to look at what happens when circulation patterns are changed by an El Niño. Some areas would be exposed to more storms and heavier rainfalls, while others might see

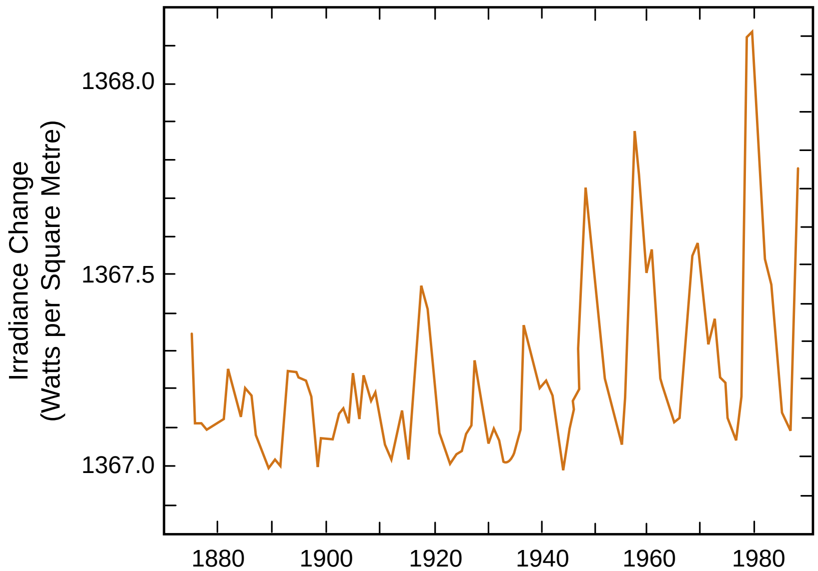
Average global temperature changes since the end of the last ice age

Although earth's climate has been remarkably stable since the last ice age ended more than 10,000 years ago, small but significant variations have occurred on scales of a few hundred to a few thousand years. These fluctuations are thought to be largely the result of changes in the output of energy from the sun.



Source: Adapted from Folland et al. *(1990)*

Estimated solar irradiance, 1874–1988



Source: Adapted from Foukal and Lean (1990)

The output of energy from the sun has been increasing since about 1850. About half of the warming of the earth's surface over the past century and a third of that since 1970 are thought to be due to this increase. Direct observations of the sun's energy output have been available from satellites only since 1978. The estimate shown here was derived using a computer model and sunspot data, and the results were calibrated against available satellite observations.

formerly reliable rainfalls give way to prolonged dry spells. Other areas might actually see improvements in their climates, but if the experience of recent El Niños is a guide, most localities would encounter at least some weather difficulties that they were poorly prepared to deal with. Over time, communities could adapt to these new conditions, but the costs could be substantial.

A second and more compelling reason for suspecting a link between greenhouse warming and weather extremes is related to the potential effects of a warmer climate on the physical processes that generate different types of weather events. Consider the example of rainfall. Precipitation is one half of the hydrological (or water) cycle. Evaporation (and transpiration from plants) is the other. A virtually certain outcome of a rise in global temperatures is a widespread increase in the amount of water that is moved through the cycle. That is because higher temperatures not only increase evaporation and transpiration but also raise the air's capacity to hold moisture. Consequently, more moisture will be available in the atmosphere to fall as rain and snow. Add to this a more unstable atmosphere due to increased convection over warmer land and sea surfaces, and the result is an increased potential for major precipitation events in many parts of the world. Because of changes in large-scale circulation patterns as well as regional differences in hydrological processes, the resulting increase in precipitation will not be spread uniformly around the world. In fact, some areas may receive less precipitation. However, climate models indicate that a warmer atmosphere will increase the amount of moisture transported into the middle and high latitudes of the Northern Hemisphere. Thus, these areas will be exposed to more rain and snow, and it is there that increases in heavy precipitation are likely to be most noticeable.

This argument, of course, looks at only the most basic (although the most important) physical relationships between temperature and rainfall. In reality, many other factors, such as soil moisture, landscape features, vegetation, season, the physics of cloud formation, and atmospheric circulation patterns must also be considered. To estimate the net effect of global warming on precipitation – or any other climate variable for that matter – we must turn to elaborate computer models of the climate system. These are known as general circulation models (or GCMs). What they do, essentially, is combine what we know about how the major climate processes work and then calculate what happens when these processes interact for a period of time and key variables, like the concentration of greenhouse gases, are changed. The results of these exercises contain a number of uncertainties and sometimes differ considerably from one model to another, but they still offer a number of useful insights into the influence of greenhouse warming on climate processes.

One point on which the models agree is that warmer climates bring an increase in average global precipitation. In addition, all of them indicate that the greatest increase will take place in the middle and higher latitudes in winter. Most of them also show an increase in soil moisture in late winter and spring in the midlatitudes of the Northern Hemisphere. In a place like Canada these factors could easily translate into a worst-case scenario for spring flooding – large accumulations of snow, heavy rains, and water-saturated soils. Indeed, the Red River flood of 1997 is a dramatic illustration of such a combination of factors.

What is even more interesting, when we look beyond the averages, is that many of the models indicate a substantial increase in heavy precipitation. Two studies, for example, show rainfall increasing by about 10–30% in most latitudes when the amount of carbon dioxide in the atmosphere is doubled. However, the worst rainfall events – the most extreme 10% – increased by 50% in some regions. A rise in the number of these events would greatly increase the danger of rapid flooding and related problems such as erosion and landslides.

Paradoxically, an increase in average global precipitation could also be accompanied by more frequent droughts in many parts of the world. This would obviously be true in those areas where circulation changes cause rainfall to decrease, but droughts could also become more frequent even where there was an increase in rainfall. One reason is that evaporation increases rapidly with temperature. In a warmer climate, increased evaporation from soils (and transpiration from plants) could therefore offset, or more than offset, any input of additional moisture from heavier rainfall. Another reason is that the disproportionate increase in extremely heavy rainfall means that more of a region's rain will come from fewer events, with a resulting increase, as several modelling studies have shown, in the number of dry days. In addition, heavy downpours do a poor job of recharging soil moisture, since much of the water is lost as surface runoff. In areas where precipitation decreases, these effects could be devastating. In a recent study of southern Europe, for example, average precipitation declined by 22% with a doubling of carbon dioxide, but the probability of a 30-day dry spell increased two to five times.

In a midlatitude country like Canada, heavy rainfalls (and snowfalls) are usually associated with storms and high winds. If extreme precipitation increases, then presumably severe storms would too. Most storm damage comes from three types of storms – tropical storms and hurricanes, large extratropical storms, and thunderstorms. However, these are caused by quite different processes, some of which may be more sensitive to a warmer climate than others. Consequently, each of these has to be looked at separately.

Tropical storms and hurricanes are potentially sensitive to greenhouse warming in that their formation is restricted to ocean areas where the sea surface temperature is greater than 27°C. Since greenhouse warming may cause a greater area of ocean to reach this temperature more often, it follows that the zone of hurricane activity could expand and the number of hurricanes could increase. There does indeed appear to be a good correlation between sea surface temperatures and hurricane frequency – according to one

FLOODING IN CANADA

- *According to the International Red Cross, floods accounted for the largest number of disasters globally between 1967 and 1991. In 1996, a "normal" year for catastrophes according to the reinsurance firm Munich Re, floods were responsible for nearly $35 billion in economic losses or about 57% of natural disaster losses globally. In Canada, federal payouts for flood losses have exceeded those for any other type of weather disaster.*

- *In Canada, flood risks vary with place and season. In early spring, rapidly melting snowpacks and ice jams pose a risk of flooding on rivers in almost every part of the country. In summer, thunderstorms are the most frequent cause of floods in all inland areas of southern Canada. These floods are the result of brief but intensive downpours and are usually restricted to a small area. Floods caused by prolonged rainstorms associated with large weather systems are most common in the spring and fall. Over a two- or three-day period, these storms can drop massive amounts of water over a large area. The rainstorm that caused the 1996 Saguenay flood, for example, dropped an average of nearly 126 mm of rain over a 100,000 km^2 area in 48 hours – enough to keep the St. Lawrence River flowing for nearly half a month at its average rate of 10,100 m^3 per second. The 1997 Red River flood, in contrast, was caused by a combination of factors – a wet autumn that left soils saturated with moisture, heavier-than-normal snowfall during the winter, and an early April blizzard that dropped another 50–70 cm of snow and freezing rain shortly after runoff had begun.*

Emerson, Manitoba, April 23, 1997

- *Overall, the risk of flooding in Canada would increase as a result of a warmer climate. This increase would come mainly from rainstorm floods, with heavier rainfall expected to come from more (and possibly more severe) thunderstorms and from fewer but larger rainstorms associated with large-scale weather systems. Shorter winters, however, may reduce the risk of snowmelt and ice-jam floods in some areas, although heavier snowfalls could add to the risk in others.*

- *Increased flooding risks will require more effective adaptation measures if damage is to be minimized. Such measures can be expensive initially, but can prevent much higher costs when heavy floods eventually occur. Manitoba, for example, has invested heavily in flood protection, mainly because the Red is naturally flood-prone in spring (due to the fact that it is a north-flowing river and its exit into Lake Winnipeg often remains frozen after upstream sections to the south have begun to thaw). The Red River Floodway, built to divert floodwaters around Winnipeg, was completed in 1968 at a cost of $68 million. Without it, the 1997 flood would have left nearly 80% of the city underwater and forced the evacuation of more than 550,000 residents. In addition, eight towns and approximately 700 rural homes are protected by dikes.*

study, record sea surface temperatures in 1995 accounted for 61% of the very large number of hurricanes that occurred that year. However, nearly half a dozen other conditions have to be met before a hurricane can develop, and it is not known whether these would become more or less common in a warmer climate. Projections from model studies of tropical storm behaviour carried out at the Max Planck Institute in Germany, though, show a significant reduction in hurricane activity, especially in the Southern Hemisphere, as a result of a warmer climate.

Hurricane intensity could also be affected by a warmer climate. That is because the theoretical limit for hurricane strength depends upon the extent of the local energy imbalance between the atmosphere and the ocean. Experiments with climate models suggest that this imbalance will increase in a warmer world, thus significantly increasing the potential intensity of hurricanes. A team led by Thomas Knutson of the U.S. National Oceanic and Atmospheric Administration, for example, used a regional hurricane prediction model to look at how hurricane behaviour in the western Pacific might be affected by a warmer climate. Their model showed a 5–10% increase in hurricane wind speeds as a result of a 2.2°C warming of the sea surface.

The current generation of general circulation models can simulate some of the characteristics of hurricane behaviour, but the amount of information they can provide is limited because hurricanes are too small for the models to simulate in detail. High resolution regional models or special hurricane models might provide some additional insight, but at the moment there are few results to go on. One of the things that GCMs can tell us, though, is whether there might be a change in the large circulation features that determine the world's major prevailing wind patterns and set limits to the poleward range of hurricanes. The evidence available from current models indicates little change in these features and hence little change in the latitudes affected by hurricanes.

What happens to hurricane behaviour in a warmer world might also depend on what happens to El Niños. Because they tend to suppress hurricane formation in the Atlantic and support it in the Pacific, stronger and more frequent El Niños could cause a geographical shift in hurricane activity, with more hurricanes occurring in the Pacific and fewer in the Atlantic. A weakening of El Niño activity, on the other hand, could shift the balance in the other direction.

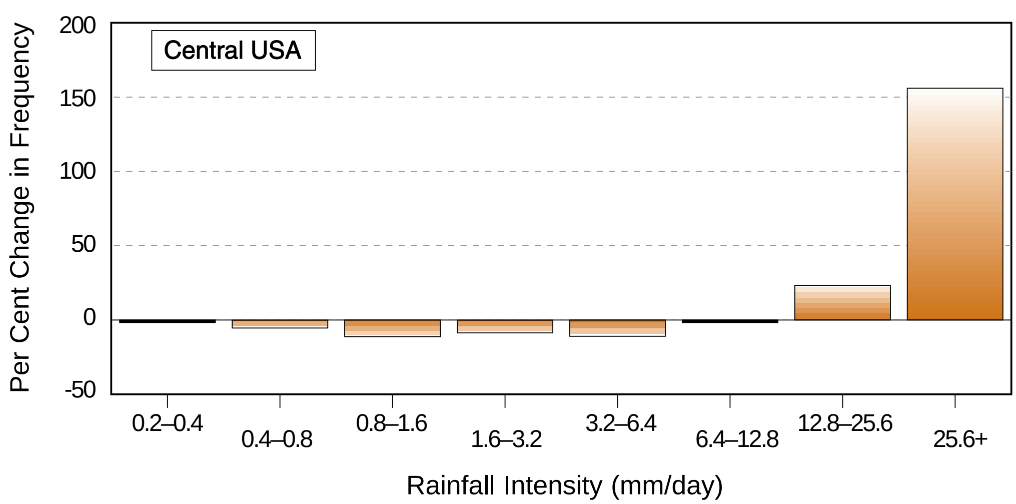
Regardless of how global warming affects either the frequency or the intensity of hurricanes, the risk of accompanying flood damage will almost certainly be accentuated by rising sea levels. Over the past century, global warming has caused the average sea level to rise by 10–25 cm, and another half-metre increase is expected by the end of the 21st century. Since flooding from hurricane storm surges usually causes more damage than wind, the risk of high death tolls and heavy property damage would actually rise even without an increase in hurricane intensity or frequency.

Extratropical storms are the large low pressure areas or depressions that commonly form and travel along the boundaries between contrasting air masses in the middle and high latitudes. The energy for these storms comes mainly from the transfer of heat between the sub-tropics and the polar regions, and the paths they follow are roughly determined by the position and contours of the sub-tropical and polar jet streams.

Global warming could affect this exchange of heat in a variety of ways. If the poles warm more than the tropics, as they are expected to do, the temperature differences that drive these storms would diminish and the number of severe storms would likely decrease. In spite of that, however, some regional temperature differences might become greater. The continents, for example, are expected to warm more than the oceans, and the increasing contrast in temperature between the two could increase the power of coastal storms. Yet another factor to be considered is water vapour. The heat given off by condensing water vapour is a source of energy for storms, and the extra water vapour held by a warmer atmosphere could provide the additional energy needed to sustain more powerful storms.

At the moment, it is unclear which of these effects would predominate, and experiments with models of warmer climates have not resolved the dilemma.

Changes in rainfall intensity with a doubling of carbon dioxide



Source: Adapted from Gordon et al. *(1992)*

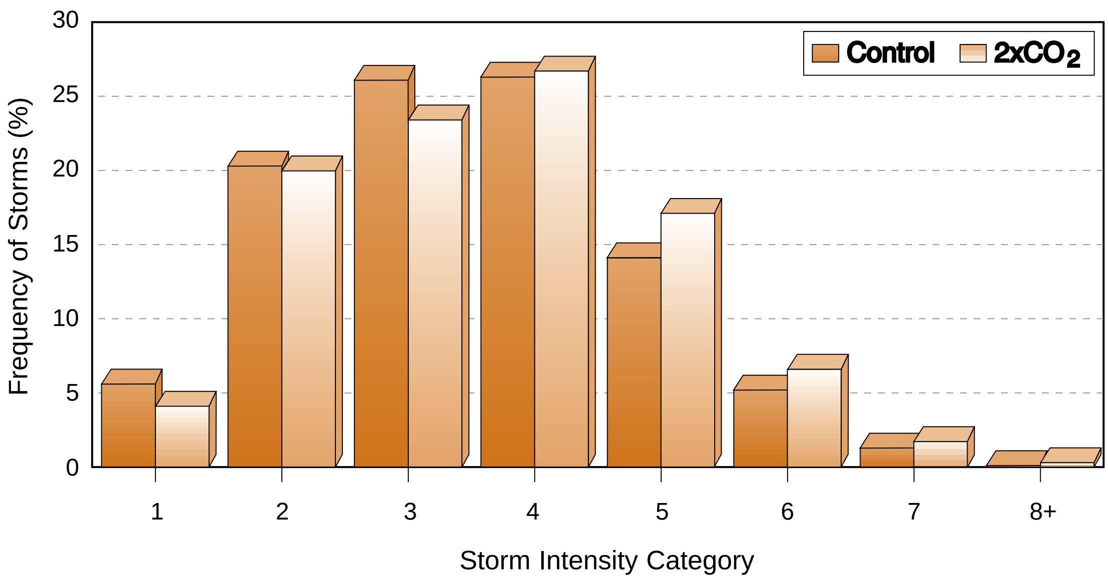
Climate models indicate that a warmer climate will bring more precipitation. Some studies also indicate that heavy rainfalls will become more frequent while light rainfalls will occur less often. Results from an Australian study, shown here for central North America, project a striking increase in the heaviest rainfall categories.

Experimenters using two models developed by the United Kingdom Meteorological Office found that the major storm tracks in the Northern Hemisphere shifted northward and storm activity intensified, particularly in the eastern Atlantic and western Europe. A Canadian model, on the other hand, showed fewer storms and no significant change in the position of the storm tracks. However, it did project a substantial increase in the number of severe winter storms.

Thunderstorms form when heating of the ground causes warm, humid air to rise and condense in colder air above. The heat from the condensing moisture causes the warm air to rise further and leads to the rapid buildup of towering cumulonimbus clouds or thunderheads. Since a warmer, moister climate will favour this process, thunderstorm activity can be expected to increase. Hotter temperatures at the surface and higher humidity levels will also make the air in thunderstorm cells rise faster and higher, creating more dynamic storm clouds and more powerful storms.

A significant byproduct of this process would be an increase in lightning. Observational evidence shows a connection between lightning activity around the world and variations in global surface temperature. Studies using the output from climate models indicate a similar linkage. An experiment at the Goddard Institute for Space Studies, for example, showed a 6% increase in lightning activity for every 1°C rise in the

Change of frequency and intensity of winter storms in a $2xCO_2$ climate



Source: Lambert (1995)

General circulation models have been used to compare storm frequencies under present climate conditions and under warmer conditions resulting from a doubling of greenhouse gases. These results, from a Canadian study, show the number of severe storms north of 30°N latitude increasing in the warmer climate while the number of less intense storms remains constant or decreases.

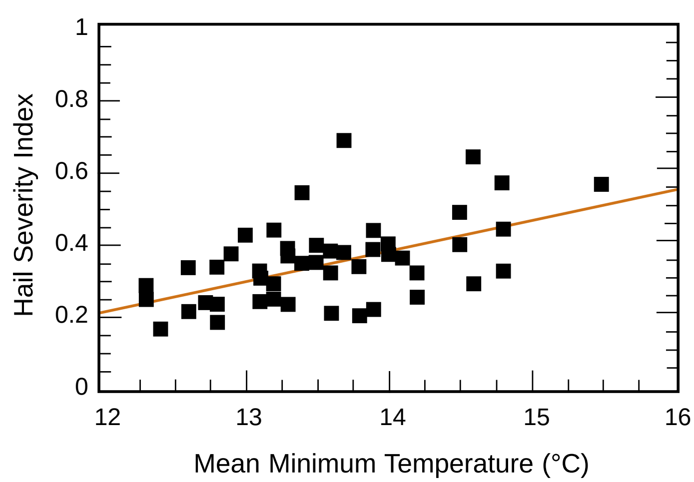
earth's average temperature. Since lightning is a frequent cause of forest fires, a warmer climate would likely increase the fire hazard, especially if summer dry spells become more prevalent as well.

Hail is also likely to occur more often. Statistical analysis of hailstorms in France shows a close correlation between average summer nighttime temperatures (which have been increasing in France as well as in many other parts of the world) and hail activity. The link between nighttime temperatures and hailstorms, which generally occur in the late afternoon, is at first hard to fathom, but it depends on a relationship that is well known to weather forecasters. Minimum nighttime temperatures are influenced by the amount of water vapour in the air, and for that reason they are a good predictor of the following afternoon's dewpoint – the temperature at which the air is saturated with water vapour. The afternoon dewpoint, in turn, is a useful predictor of unsettled weather, since it indicates how much water vapour is available to fuel a developing storm. The rise in summer minimum temperatures is therefore an indicator that the atmosphere is more prone to thunderstorm, and hence hail, activity.

Tornadoes and powerful supercell thunderstorms require special additional conditions for their formation, particularly an inflow of cold, dry air at higher altitudes. Whether or not these conditions would become more prevalent in a warmer climate is unknown. The large general circulation models used for studies of climate change tell us little about the behaviour of thunderstorms because individual thunderstorm cells are much smaller than the smallest details these models can reproduce. However, an analysis of tornadoes in the Prairie Provinces has shown a tendency for tornado frequency to increase in the spring and early summer in step with increases in average monthly temperature. It is therefore reasonable to assume that tornado outbreaks would occur more often on the prairies as a result of a warmer climate. Techniques that link local weather phenomena to larger-scale climate patterns may provide further insight into thunderstorm and tornado behaviour in a warmer world.

Finally, what about temperature? As average temperatures rise, it would be logical to expect the number of extremely hot days to increase. However, there are good reasons for believing that the increase could be considerable and out of all proportion to the

Mean summer minimum temperature and hail severity in France



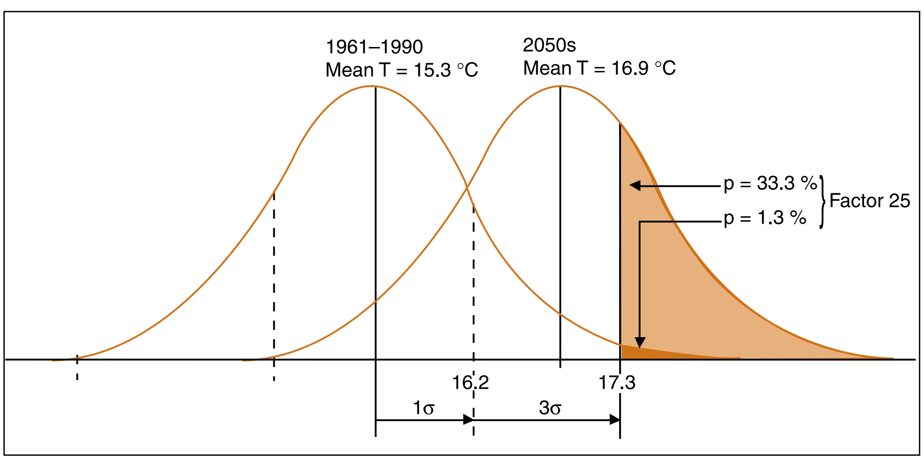
Source: Adapted from Dessens (1995)

Research into hailstorms in France shows hail activity increasing when average overnight low temperatures are higher. This linkage suggests that hailstorms (and severe thunderstorms) would occur more often in a warmer climate.

increase in average temperature. One of these reasons involves the mathematical behaviour of frequency distributions. The left-hand curve in the graph below shows a typical distribution pattern for measurements of average summer temperatures. This particular graph is for a location in central England where weather records have been kept for 300 years, but graphs for other places would show much the same pattern. The plot fits the familiar bell curve, with values near the average occurring most often and more extreme values occurring less. In a warmer climate where temperatures vary according to the same pattern, the curve keeps the same shape but moves to the right, with some interesting results. In this example, the average temperature has increased by 1.6°C, but if we compare the number of summers with average temperatures above 17.3°C, we see an enormous change between the two graphs. What had been a very low value in the left-hand curve becomes a very high value in the right-hand curve. The actual difference, measured by comparing the areas under each of the curves to the right of the 17.3° line, amounts to a factor of 25. What this means is that an extremely warm summer that could be expected to occur only once in every 75 years could be expected once every 3 years in the warmer climate. This is a hypothetical example, but it does show that a small change in the average can result in very large changes in the extremes.

Another reason for expecting a substantial increase in high temperature extremes comes from experiments with climate models, which show a large increase in the number of extremely warm days and heat waves as a result of global warming. One Canadian study suggests that an increase of 4°C in Toronto's average temperature would likely increase the risk of summer days with temperatures exceeding

Changes in the Frequency of Extreme Temperatures with a Change in the Mean Temperature



Source: Adapted from Munich Re (1996)

Small changes in the average can result in large changes in extremes. In this example taken from central England, an increase of 1.6°C in the average summer temperature causes the probability of a very warm summer (exceeding 3 standard deviations) to increase from once in 75 years (a probability of 1.3%) to once in 3 years (a probability of 33.3%).

30.5°C from 1 in 10 to almost 1 in 2. Estimates for other parts of the world show similar results. An Australian study, for example, concluded that a 0.5°C rise in average temperature would increase the number of extremely hot days (above 35°C) in the state of Victoria by 25%. With a rise of 1.5°C, the number of hot days would increase by 50–100%.

But if a warmer climate increases extremes at the high end of the temperature scale, it should also logically reduce extremes at the low end. Simulations with models tend to bear this out. In the Australian study, for example, the possibility of a 5-day cold spell below 0°C was reduced by 20–40%, depending on the region considered. Similarly, calculations by Canadian climate modeller Francis Zwiers showed that the lowest temperature that Winnipegers might expect to face in a twenty-year period would rise from the present –45°C to a balmier –33°C in the kind of climate that could be expected if carbon dioxide concentrations in the atmosphere were to double.

Implications of an Increase in Weather Extremes

A possible connection between global warming and extreme weather is of more than academic interest. The economic, human, and ecological costs of even a small long-term increase in extremes would be substantial. Just how substantial can be visualized if we consider what extreme weather already costs us.

In Canada, individual floods have caused as many as 79 deaths (Hurricane Hazel in 1954), displaced more than 25,000 people (the Red River flood of 1997), and resulted in property damage and other costs exceeding $1 billion (the Saguenay flood of 1996). A single hailstorm caused $120 million worth of damage in Winnipeg in July 1996, and insured losses from other hailstorms have gone as high as $400 million, as they did in Calgary in 1991. The massive snowstorm that struck Victoria and B.C.'s lower mainland at the end of 1996 resulted in an estimated $200 million in losses, caused 1700 people to seek emergency food and shelter, left 150,000 homes without power, and blocked some roads for as long as 10 days. The storm also contributed to 500 avalanches and 65 pollution spills. The most destructive single weather event to date, however, was the eastern ice storm of January 1998, which left 25 dead, stranded nearly 3 million people without heat or electricity, forced the mobilization of 15,000 troops, and caused an estimated $2 billion in damage. It should be remembered, though, that even relatively small-scale events can result in impressively large repair bills. A 90-minute downpour in Ottawa in August 1996, for example, caused more than $20 million in insured losses plus additional costs for repairs to roads and sewers.

At the other end of the hydrological spectrum, drought can cause agricultural losses in the billions. In 1988, Canada's grain production was reduced by nearly a third because of drought, and the resulting export losses were estimated at $4 billion. Hot, dry summers also provide ideal conditions for forest fires, and the difference between fire management costs in a good forest fire year as opposed to a bad one can amount to as much as $200 million or more.

Internationally, the costs of extreme weather are often higher. In 1996 a series of floods in China resulted in more than 3000 deaths, left 5 million homeless, closed 8000 factories, and killed tens of thousands of animals, resulting in economic losses estimated at US$20 billion. The North Korean famine, which reached catastrophic proportions in 1997, was in part the result of floods in 1995 and 1996 followed by drought in 1997. In Jamaica, losses from Hurricane Gilbert in 1988 amounted to about one third of the country's gross national product, and more than 40% of the island's housing was destroyed. Recovering from such disasters places a major strain on countries with limited economic means and may intensify the demand on resource bases and ecosystems that are already overstressed. Aid from industrialized countries such as Canada also plays an essential role in disaster recovery. If weather disasters become more frequent, the demand for aid will increase accordingly. If an increase in weather extremes is persuasively linked to greenhouse warming and climate change, the moral obligation of industrialized countries to provide disaster relief will also be considerably greater.

The escalating costs of weather-related property losses over the past couple of decades are already straining the resources of the world's insurance industry. Since 1987 it has had to deal with at least one $1 billion disaster almost every year. Some large insurance and re-insurance companies have already been forced into bankruptcy by weather-related claims, and some, such as Lloyd's of London, have faced solvency crises at least in part because of losses from weather disasters. If these trends continue, insurers will have to raise premiums, limit their liability, or even back out of existing markets that have become too risky, as many hurricane insurers have in the Carribean. Increasingly, governments may have to provide protection against risks that insurers will no longer cover. Governments, and hence taxpayers, will also face increasing costs for emergency services, disaster relief, and disaster-related foreign aid.

Other sectors of society and the economy would also face rising costs in order to counter the risks of more dangerous and destructive weather. Structures such as buildings, dams, bridges, and hydro towers would have to be built to withstand heavier stresses, transportation services would face more frequent interruptions and the possibility of greater damage to their equipment and infrastructure, and farmers would have to improve irrigation and alter cropping practices to deal with the increased occurrence of drought. Failure to take these precautions would only result in higher economic costs, greater social disruption, and increased loss of life when a disaster eventually strikes.

The ecological impacts of extreme weather on natural and agricultural ecosystems should not be overlooked either. Events such as the 1998 ice storm in eastern Canada or the 1987 wind storm in southern England, for example, weaken or destroy millions of trees which, in their healthy state, provide food and habitat for wildlife and a sink for absorbing carbon dioxide. Droughts increase the risk of forest fires and hasten the dieback of forests weakened by other stresses. Floods wash away scarce topsoil and often diminish the productivity of agricultural lands. Losses from individual events may not be an insurmountable problem, but over time and in combination with other impacts, the cumulative effect of severe weather on ecosystems could be considerable.

Food security presents a particularly worrisome problem, given the continuing growth of the world's population and the levelling off in production of key foodstuffs such as wheat and rice. Increased crop damage from droughts, floods, and storms could make famines not only more frequent but far more difficult to deal with.

Responses

It is clear that weather extremes are becoming an increasingly serious problem for our society. There is also a reasonable probability that global warming will make the problem worse. The difficulty is that we don't know for sure the extent to which the present wave of extremes is a natural climatic phenomenon, nor do we know the real potential for the intensification of extreme weather in a warmer climate. To diminish these uncertainties, we have to devote much more scientific effort to the study of severe weather as a feature of climate. This effort will have to focus on three areas in particular.

First, we need to have a much better grasp of present and emerging trends in severe weather. One of the chief difficulties here is that extreme weather events, by definition, occur infrequently. They are also usually limited in area and often short in duration. Consequently, they tend to leave a weak statistical trail or none at all. However, the occurrence of many of these events can be inferred through analysis of the larger-scale weather patterns to which they are related. The existence of storms and the intensity of winds, for example, can be estimated from regional pressure patterns. There are also problems with the comparability or quality of historical climate records. Instruments change over time and so do the physical characteristics of weather stations and their surroundings. These factors can introduce false trends into long-term climate analyses, but careful analysis can detect these problems and it is often possible to introduce statistical corrections to compensate for them.

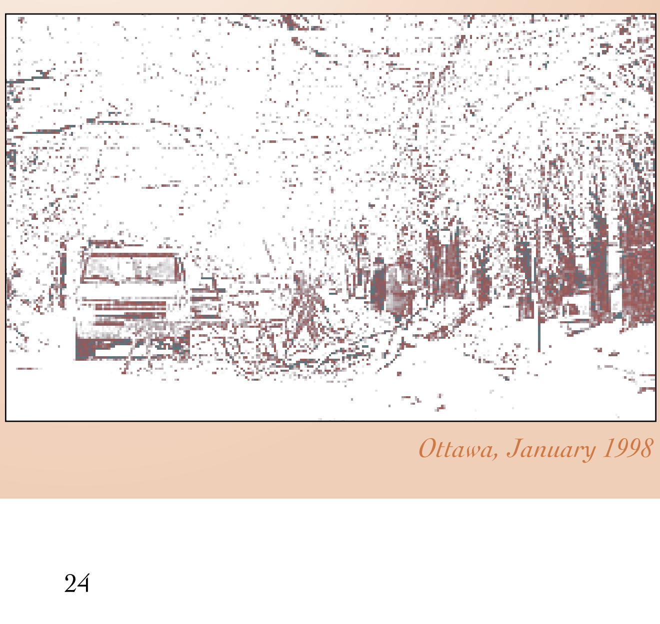
The second requirement is for a better understanding of natural climatic variability. Some of this can be derived from the instrumental climate record – that is, the record of weather observations taken with properly calibrated instruments under controlled conditions. For some places, this information may extend back a century and a half or more, but for much of the world it is considerably shorter. To detect longer-term swings in climate, it is necessary to turn to palaeoclimatic data, the information that comes from tree rings, sediments, ice cores, fossils, and other natural

THE 1998 ICE STORM

Freezing rain is a common experience in most parts of Canada. Although Victoria averages only 2 hours of it per year, places such as Yellowknife, Regina, and Toronto get 35 hours in the course of an average year, while St. John's endures a formidable 148 hours. Episodes of freezing rain are generally short, but from time to time they can develop into major ice storms that are notable both for their sparkling beauty and for the crushing weight of ice they leave on power lines and trees. Damaging ice storms have occurred as recently as 1986 in Ottawa and 1984 in St. John's, but the storm that struck much of eastern Canada in January 1998 was remarkable for its persistence, its extent, and, ultimately, the magnitude of its destruction. Over a period of six days, up to 100 mm of freezing rain fell intermittently over an area that at one point extended from central Ontario to Prince Edward Island. Downed power lines left nearly three million people without electricity. The Montreal area was worst affected, and some localities south of the city were without power for as long as five weeks. The storm was blamed for 25 deaths, and with initial estimates of damages in the range of $1–2 billion, it is by far the costliest weather catastrophe in Canadian history.

Freezing rain occurs when warm, moist air that is above the freezing point overlies cold air at ground level that is below the freezing point. Because rain falling from the warmer air is supercooled as it passes through the colder layer, it freezes instantly on contact with the ground. This situation commonly occurs along fronts where warm and cold air masses on opposite sides of the freezing point meet, but the fronts generally move along quickly and the freezing rain conditions are short-lived. The 1998 ice storm, however, was the product of quite unusual conditions – an El Niño–related sub-tropical jet stream that brought warm, moist air out of the American south, a steady flow out of the northeast that maintained a shallow layer of cold air in the lowlands of the Ottawa and St. Lawrence valleys, and finally a stagnant ridge of high pressure over the Atlantic that kept the whole system in place.

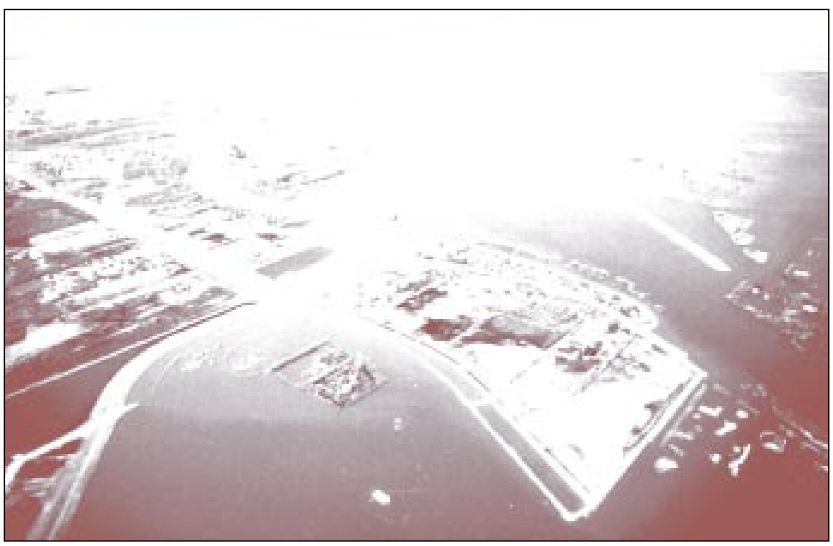
In a warming climate, milder winter temperatures could possibly cause an increase in freezing rain in places where average daily temperatures begin to meander around the freezing point instead of remaining firmly below it. However, this does not necessarily translate into the more frequent occurrence of events such as the ice storm of 1998. This was the result of the simultaneous occurrence of at least three special factors, and there is no compelling reason at the moment to assume that a warmer climate would make it significantly more likely for such an event to happen again.



Ottawa, January 1998

evidence that may bear an imprint of past climate changes. Quite a bit can be learned in this way about previous variations in temperature and rainfall, although little can be found out about other extremes such as storms. Historical documents, such as memoirs, narratives, ships' logs, and insurance records, can also provide direct, though qualitative, evidence of severe weather in the past. Indirect historical evidence, such as records of grain prices, can also point to the occurrence of droughts and wet spells and other climatic factors that affect the supply of agricultural commodities.

Finally, the possible connection between global warming and various types of weather extremes needs to be explored more thoroughly. We know of mechanisms by which global warming could increase the frequency or intensity of severe weather, but other physical processes could also have an important effect on the outcome. To determine the net effect of the interactions between these processes, we must rely on climate models, but our present general circulation models cannot produce the fine detail needed to study regional climate behaviour and small-scale features such as thunderstorms and hurricanes. To get around this problem, climate modellers are developing techniques for estimating the occurrence of weather extremes from the larger-scale patterns that the models now produce. More can also be learned by using physical process models to study the dynamics of events such as hurricanes and thunderstorms under conditions that might prevail as a result of global warming. Yet another line of inquiry involves the use of high resolution regional models to get a better look at how the climates of specific areas would behave under different kinds of warming scenarios. Such regional studies are particularly important, because



Climate adaptation measures, such as Winnipeg's Red River Floodway, shown here in April 1997, are one way of dealing with weather extremes. Although these measures may be expensive, the return in damages avoided is usually much greater. If adaptive measures are overwhelmed by unexpectedly extreme impacts, however, communities can be faced with sudden and catastrophic costs. Improved adaptive measures – such as the expansion of flood control systems, a tightening of land use regulations, and additional reinforcement of buildings and other structures – would be an essential response to any increase in weather extremes.

the effects of global warming on regional climates and particularly on extreme weather is likely to vary substantially from one part of the world to another.

Regardless of the outcome of these studies, it is already clear that modern societies are becoming more vulnerable to economic damage from weather extremes as their infrastructures become more elaborate and their populations grow larger and more concentrated. In fact, one of the lessons of the 1998 ice storm and the recent Red River and Saguenay floods is that we in Canada have underestimated both the risks and the consequences of at least some of the major weather hazards that we now face. It is important, therefore, for us to reassess our estimates of the risks of weather disasasters and our ability to cope with them. That means reviewing our calculations of the probabilities of different kinds of weather extremes to determine whether the event that now has an estimated probability of occurring once in 100 years should be upgraded to, say, a 1 in 50 probability. That kind of change would, in turn, necessitate a serious second look at many of our zoning laws, building codes, and engineering standards as well as our plans and capabilities for dealing with emergencies. Evidence of a significant link between global warming and extreme weather events would make it even more imperative to conduct such a review, and it would set the bar even higher when it came to defining acceptable levels of protection.

Certainly there is evidence of increasing extremes in some parts of the world. Although these increases could simply be a result of natural climate variability, they are also consistent with many of the changes expected as a result of greenhouse warming.

Drawing Conclusions

Is global warming loading the dice in favour of extreme weather? Certainly there is evidence of increasing extremes in some parts of the world. Although these increases could simply be a result of natural climate variability, they are also consistent with many of the changes expected as a result of greenhouse warming. We also know that there are plausible physical mechanisms by which global warming could increase both the frequency and the intensity of some kinds of extreme weather events. Our understanding of climate processes, for example, suggests very strongly that heavy rainfalls and thunderstorms will be more common in a warmer climate. Heat waves and hot days would also increase. As for other types of extreme events, such as extratropical storms and hurricanes, the arguments are conflicting.

Finding conclusive proof that a connection between greenhouse warming and weather extremes does or does not exist will not be easy, at least for another decade or two. For one thing, we simply do not know enough about natural climate variability to have a reliable benchmark of comparison. For another, global warming is still in its early stages. Most scientific studies of global warming are based on a doubled-CO_2 atmosphere – one in which atmospheric concentrations of carbon dioxide are double the pre-industrial level of approximately 280 parts per million (ppm) or some more recent value. The present concentration of about 360 ppm is only about 30% above the pre-industrial base. If we add in the effects of other greenhouse gases, we are still only about halfway to the equivalent of a CO_2 doubling. In addition, the effect of the increase in greenhouse gases is to some extent offset by the sunlight-scattering effects of high concentrations of sulphate aerosols over and downwind of the industrialized regions of the globe. Another problem is that natural climate variability will sometimes reinforce and sometimes moderate any effects that greenhouse warming might have on extreme weather formation. As a result, changes in the occurrence of extreme weather events will be irregular and the detection of trends will be complicated.

Carbon dioxide concentrations are expected to reach the doubling point within the next 50–75 years, and they will continue rising unless decisive action is taken to stabilize or reduce emissions. Studies with transient climate change models that simulate the

THE POSSIBILITY OF SURPRISES

Models and other scientific tools can indicate some of the more likely outcomes of climate change, but we cannot be sure that they will identify all of them. Climate is the product of a bafflingly complex array of processes, and the possibility of major surprises is always present. Climates of the past, rather than changing gradually, have sometimes shown a tendency, at least regionally, to switch abruptly to a radically different mode. A surprise of this sort could have devastating consequences, both for natural ecosystems and human societies.

The course of climate change could veer into unanticipated territory, for example, if extensive thawing in the world's subpolar regions released the vast amounts of methane now locked up as frozen hydrates in the permafrost of these areas. This would result in a rapid intensification of the greenhouse effect that would not only increase extremes of heat but would greatly distort other climate patterns in many parts of the globe.

Another possibility is related to the processes that drive the "Atlantic conveyor" – the sub-surface flow of warm water into the North Atlantic that gives western Europe its mild winters. The warm water is drawn northward to replace cold salty water that plunges to the ocean floor at various locations in the northern North Atlantic. This process of deep water formation is the essential driving mechanism for the Atlantic conveyor, but it only works when the water is very salty and cold. Either of these factors could be easily altered by a warming climate. Were the Atlantic conveyor to weaken or shut down entirely, the climate of western Europe would cool dramatically and the climate of the Northern Hemisphere generally would become much more variable. Such a change could take place within decades.

Some recent studies with combined ocean and climate models show the Atlantic conveyor weakening and then returning to its former strength as the carbon dioxide concentration of the atmosphere gradually increases to double the pre-industrial value. At four times the pre-industrial concentration, however, the conveyor remains weak for up to 500 years. Other studies suggest that the Atlantic conveyor could become less stable and more variable in a warmer world.

gradual evolution of an enhanced greenhouse effect suggest that its impact on global climate will become increasingly apparent somewhere between 2010 and 2030 – well within the lifetime of children born today. If greenhouse warming is forcing an increase in weather extremes, it should be clear by then, and the kinds of extremes that we are seeing now could become increasingly common. In the meantime, we must do as much as we can, not only to increase our understanding of future risks but also to improve our adaptation to present hazards. An ounce of prevention is still worth a pound of cure.

Bibliography

Is Extreme Weather Becoming More Common?

Born, K., 1996. Tropospheric warming and changes in weather variability over the northern hemisphere during the period 1967–1991, *Meteorology and Atmospheric Physics,* **59,** 201–215.

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

Dessens, J., 1995. Severe convection weather in the context of a nighttime global warming. *Geophysical Research Letters,* **22,** 1241–1244.

Environment Canada, 1995. *The state of Canada's climate: monitoring variability and change.* Environment Canada, Downsview, Ontario.

Etkin, D. Beyond the year 2000: More tornadoes in western Canada? Implications from the historical record. *Natural Hazards,* **12,** 19–27.

Kaas, E., T-S. Li, and T. Schmith, 1996. Statistical hindcast of wind climatology in the North Atlantic and northwestern European region. *Climate Research,* **7,** 97–110.

Karl, T.R., R.W. Knight, and N. Plummer, 1995. Trends in high-frequency climate variability in the twentieth century. *Nature,* **377,** 217–220.

Karl, T.R., R.W. Knight, D.R. Easterling, and R.G. Quayle, 1996. Indices of climate change for the United States. *Bulletin of the American Meteorological Society,* **77,** 279-292.

Lambert, Steven J., 1996. Intense extratropical northern hemisphere winter cyclone events: 1899–1991. *Journal of Geophysical Research,* **101,** 21219–21325.

Landsea, C.W., N. Nicholls, W.M. Gray, and L.A. Avila, 1996. Downward trend in the frequency of intense Atlantic hurricanes during the past five decades. *Geophysical Research Letters,* **23,** 1697-1700.

London, S.J., S.G. Warren, and C.J. Hahn, 1991. Thirty-year trend of observed greenhouse clouds over the tropical oceans. *Advances in Space Research,* **11(3),** 45–49.

McCulloch, J. and D. Etkin, eds., 1993. *Proceedings of a workshop on improving responses to atmospheric extremes: The role of insurance and compensation.* Environment Canada, Downsview, Ontario.

Munich Re, 1997. *Topics: Annual review of natural catastrophes.* Munich Re, Munich.

Nicholls, N., G.V. Gruza, J. Jouzel, T.R. Karl, L.A. Ogallo, and D.E. Parker, 1996. Observed climate variability and change. In *Climate change 1995: The science of climate change.* Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds. Cambridge University Press, Cambridge.

Ostby, F.P., 1993. The changing nature of tornado climatology. In *Preprints, 17th conference on severe local storms, October 4–8, 1993, St. Louis, Missouri,* pp. 1–5.

Pearce, D.W., W.R. Cline, A.N. Achanta, S. Fankhauser, R.K. Pachauri, R.S.J. Tol, and P. Vellinga, 1996. The social costs of climate change: Greenhouse damage and the benefits of control. In *Climate change 1995: Economic and social dimensions of climate change.* Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. J. Bruce, H. Lee, and E. Haites, eds. Cambridge University Press, Cambridge.

Pielke, Roger A., Jr. and Christopher W. Landsea, 1997. Normalized hurricane damages in the United States: 1925–1995. Draft paper. National Center for Atmospheric Research, Boulder, Colorado.

Schmidt, H. and H. von Storch, 1993. German Bight storms analysed. *Nature,* **365,** 791.

Suppiah, R. and K.J. Hennessy, 1996. Trends in the intensity and frequency of heavy rainfall in tropical Australia and links with the southern oscillation. *Australian Meteorological Magazine,* **45,** 1–18.

Tsonis, A.A., 1996. Widespread increases in low-frequency variability of precipitation over the past century. *Nature,* **382,** 700–702.

Von Storch, H., J. Guddak, K.A. Iden, T. Jùnsen, J. Perlwitz, M. Reistad, J. de Ronde, H. Schmidt, and E. Zorita, 1993. *Changing statistics of storms in the North Atlantic?* Report No. 116. Max-Planck-Institut für Meteorologie, Hamburg.

Natural Variability

Burroughs, W.J., 1992. *Weather cycles: Real or imaginary?* Cambridge University Press, Cambridge.

Environment Canada, 1995. *The state of Canada's climate: monitoring variability and change.* Environment Canada, Downsview, Ontario.

Folland, C.K., T.R. Karl, and K.Ya. Vinnikov, 1990. Observed climate variations and change. In *Climate change: The IPCC scientific assessment.* J.T. Houghton, G.J. Jenkins, and J.J. Ephraums, eds. Cambridge University Press, Cambridge.

Foukal, P. and J. Lean, 1990. An empirical model of total solar irradiance variation between 1874 and 1988. *Science,* **247,** 556–558.

Haigh, J.D., 1994. The role of stratospheric ozone in modulating the solar radiative forcing of climate. *Nature,* **370,** 544–546.

Haigh, J.D., 1996. The impact of solar variability on climate. *Science,* **272,** 981-984.

Hansen, J.E., A. Lacis, R. Ruedy, M. Sato, and H. Wilson, 1993. How sensitive is the world's climate? *National Geographic Research and Exploration,* **9,** 142–158.

Lean, J., J. Beer, and R. Bradley, 1995. Reconstruction of solar irradiance since 1610: Implications for climate change. *Geophysical Research Letters,* **22,** 3195–3198.

Morton, Oliver. The storm in the machine. *New Scientist,* **157** (2119), 22–27.

Shine, K.P., Y. Fouquart, V. Ramaswamy, S. Solomon, and J. Srinivasan, 1995. Radiative forcing. In *Climate change 1994.* J.T. Houghton, L.G. Meira Filho, J. Bruce, H. Lee, B.A. Callander, E. Haites, N. Harris, and K. Maskell, eds. Cambridge University Press, Cambridge.

Greenhouse Warming and Weather Extremes

Bengtsson, L., M. Botzet, and M. Esch, 1996. Will greenhouse gas–induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes? *Tellus,* **48A,** 57–73.

Broccoli, A.J., S. Manabe, and J.F.B. Mitchell, 1995. Comments on "Global climate change and tropical cyclones:" Part II. *Bulletin of the American Meteorological Society,* **76,** 2244–2245.

Carnell, R.E., C.A. Senior, and J.F.B. Mitchell, 1996. An assessment of measures of storminess: simulated changes in northern hemisphere winter due to increasing CO_2. *Climate Dynamics,* **12,** 467–476.

Cubasch, U., J. Waszkewitz, G. Hegerl, and J. Perlwitz, 1995. Regional climate changes as simulated in time-slice experiments. *Climate Change,* **31,** 273–304.

Dessens, J., 1995. Severe convection weather in the context of a nighttime global warming. *Geophysical Research Letters,* **22,** 1241–1244.

Emanuel, K.A., 1995. Comments on "Global climate change and tropical cyclones:" Part I. *Bulletin of the American Meteorological Society,* **76,** 2241–2243.

Etkin, D. Beyond the year 2000: More tornadoes in western Canada? Implications from the historical record. *Natural Hazards,* **12,** 19–27.

Fowler, A.M. and K.J. Hennessey, 1995. Potential impacts of global warming on the frequency and magnitude of heavy precipitation. *Natural Hazards,* **11,** 283–303.

Gordon, H.B., P.H. Whetton, A.B. Pittock, A.M. Fowler, and M.R. Haylock, 1992. Simulated changes in daily rainfall intensity due to the enhanced greenhouse effect: implications for extreme rainfall events. *Climate Dynamics,* **8,** 83–102.

Gregory, J.M. and J.F.B. Mitchell, 1995. Simulation of daily variability of surface temperature and precipitation over Europe in the current and 2 x CO_2 climates using the UKMO climate model. *Quarterly Journal of the Royal Meteorological Society,* **121,** 1451–1476.

Hall, N.M.J., B.J. Hoskins, P.J. Valdes, and C.A. Senior, 1994. Storm tracks in a high resolution GCM with doubled CO_2. *Quarterly Journal of the Royal Meteorological Society,* **120,** 1209–1230.

Hennessey, K.J. and A.B. Pittock, 1995. Greenhouse warming and threshold temperature events in Victoria, Australia. *International Journal of Climatology,* **15,** 591–612.

Kattenberg, A., F. Giorgi, H. Grassi, G.A. Meehl, J.F.B. Mitchell, R.J. Stouffer, T. Tokioka, A. J. Weaver, and T.M.L. Wigley, 1996. Climate models – projections of future climate. In *Climate change 1995: The science of climate change.* Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. J. T. Houghton, L. G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds. Cambridge University Press, Cambridge.

Knutson, T.R., R.E. Tuleya, and Y. Kurihara, 1998. Simulated increase of hurricane intensities in a CO_2-warmed climate. *Science,* **279,** 1018–1020.

Lambert, S.J., 1995. The effect of enhanced greenhouse warming on winter cyclone frequencies and strengths. *Journal of Climate,* **8,** 1447–1452.

Lighthill, J, G. Holland, W. Gray, C. Landsea, G. Craig, J. Evans, Y. Kurihara, and C. Guard, 1994. Global climate change and tropical cylones. *Bulletin of the American Meteorological Society,* **75,** 2147–2157.

O'Brien, J.J., T.S. Richards, and A.C. Davis, 1996. The effect of El Niño on U.S. landfalling hurricanes. *Bulletin of the American Meteorological Society,* **77,** 773–774.

Price, C. and D. Rind, 1994. Possible implications of global climate change on global lightning distributions and frequencies. *Journal of Geophysical Research,* **99,** 10823–10831.

Saunders, M.A. and A.R. Harris, 1997. Statistical evidence links exceptional 1995 Atlantic hurricane season to record sea warming. *Geophysical Research Letters,* **24,** 1255–1258.

Sun, De-Zheng, 1997. El Niño: A coupled response to radiative heating? *Geophysical Research Letters,* **24,** 2031–2034.

Whetton, P.H., A.M.Fowler, M.R. Haylock, and A.B. Pittock, 1993. Implications of climate change due to the enhanced greenhouse effect on floods and droughts in Australia. *Climate Change,* **25,** 289–317.

Zwiers, F.W., 1998. Changes in the extremes of the climate simulated by CCC GCM2 under CO_2 doubling. *Journal of Climate* (in press).

Implications

Etkin, D., 1997. Climate change and extreme events: Canada. Draft paper. Environmental Adaptation Research Group, University of Toronto.

Pearce, D.W., W.R. Cline, A.N. Achanta, S. Fankhauser, R.K. Pachauri, R.S.J. Tol, and P. Vellinga, The social costs of climate change: Greenhouse damage and the benefits of control. In *Climate change 1995: Economic and social dimensions of climate change.* Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. J. Bruce, H. Lee, and E. Haites, eds. Cambridge University Press, Cambridge.

Street, R., 1997. Weather impacts in Canada. Paper presented at the Workshop on the Social and Economic Impacts of Weather, Boulder, Colorado, 2–4 April.