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North American Climate Change and Weather Extremes

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Prologue

The United States-Canada Symposium on Climate Change and Weather Extremes was convened in Atlanta, Georgia in October 1999 by Environment Canada, the US Environmental Protection Agency and the US National Weather Service, with additional financial support from the Climate Change Action Fund (Canada). The Symposium focused on the issue of extreme weather events: how to define them, how to predict them, how to cope with their impacts on human and ecological systems, and how they may be influenced by climate change. The meeting brought together an array of experts from diverse communities, including resource managers and planners who are affected by extreme events, impacts and adaptation researchers, climate modelers, climatologists, and computer hardware developers.

The goal of the symposium was to identify existing capabilities and near-term needs in understanding weather and climate extremes, that, if met, would improve our ability to assess the human impacts of extreme weather. To advance this goal, the symposium was designed to:

- review current capacities for identifying weather extremes in the climate system;
- assess current understanding of the relationship between weather extremes, climate variability, and climate change;
- examine the vulnerabilities of American and Canadian societies to weather extremes; and
- determine the steps needed to advance the modeling and assessment of weather extremes.

This *Proceedings* includes 14 papers from meeting participants. Taken together with the companion *Research Agenda,* this *Proceedings* provides an overview of extreme events in the context of climate change and sets forth the research needs identified across wide ranging communities of scientists and policy makers.

Climate Extremes In Canada

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Introduction

The purpose of this paper is to both describe what we know about climate extremes in Canada and to provide some discussion points on the nature of future work on climate extremes. Because of Canada’s high latitude location, the type of climate extreme that is significant, may differ from much of the rest of the world. Because of its large area, low population density and sparse climate networks, availability of Canadian data is important for global analyses.

Available Canadian Data

The prime data concern for climate change analysis projects is the homogeneity of the time series. Trends and even changes in variability are small and similar in magnitude to changes induced by even innocuous appearing changes to the measurement program. It is strongly recommended that only data that has undergone homogeneity screening be included in the analysis of climate extremes. Vincent (1999) describes a method used to adjust temperature data for about 200 long-record stations in Canada and Mekis and Hogg (1999) describe a technique that has been used to rehabilitate daily precipitation data from approximately 500 stations. These data are being used in the production of a gridded time series for Canada of monthly temperature and precipitation for this century, using an approach described by Hogg et al. (1996). The grid values will then be used to estimate other water balance parameters (evapotranspiration, runoff, Palmer Drought Severity Index, etc.) for the grid. Computation of time series of the area of Canada affected by various extreme conditions has been performed using this gridded dataset.

Definition of Climate Extremes

What is a climate extreme, anyway? One of the difficulties in coming to grips with this question is that it means different things to different people.

To members of the public, a climate event is considered extreme if:

- it cost them money or injury
- they haven’t experienced it in the last 10 years
- a similar event hasn’t happened in their state or province in the last 5 years
- a similar event hasn’t happened in their country in the last year.

An “Impacts” scientist brings more objectivity but still introduces a wide range of criteria to define extreme events. They are often defined according to some threshold associated with significant loss of money, quality of life or life itself. But such criteria are as dependent upon societal changes as on changes in the physical characteristics of the climate event. Urban flooding occurs when the capacity of structures, designed to varying standards (e.g. 5-25 year return periods) and in varying states of repair, fail. Heat waves may be defined in terms of hospital admissions, which are influenced by changes in population, demographics and record keeping. Building damage due to wind or snow loads is dependent on local building codes, construction practices, age of the structures and changes in exposure. And so on.

The climatologist insists upon absolute objectivity but sometimes sacrifices relevance, at least in terms of societal importance. To assess the rarity of an event at a specific location, analyses are confined to fixed locations, which often results in the examination of a mixture of “ordinary” and extreme events, from an impact perspective. To increase sample size, the climatologist may define the extreme event as the biggest or even 10 biggest occurrences per year of some parameter or examine the frequency of measurements above a threshold expected to be exceeded at least once and maybe as many as 10 times per year. An even greater distortion occurs when the climatologist attempts to increase sample size through removal of the annual cycle by examining the biggest departures from the mean value for the time of year. Such a procedure can identify extreme events that are climatologically noteworthy but which have little impact on society, such as an autumn heat wave.

Regional analyses allow expansion of the selection process to include truly rare events (e.g. the biggest per year among many stations, the frequency of network occurrence exceeding the point 10-year return period amount or the proportion of area affected by low probability conditions). However, the region being analyzed must be climatically homogeneous and stations must be spaced widely enough to be independent while having coincident, long records.

The simultaneous occurrence of fairly ordinary conditions to produce extreme events is one last complicating factor. Temperatures slightly below freezing for a week are not unusual in January in southeastern Canada and even the occurrence of 10-25 mm of precipitation on a January day is not unexpected. But to have both these conditions met for five consecutive days over a large geographic area (SW Quebec and SE Ontario, January 1998) generating 50-100 mm of freezing rain, creates an unquestioned extreme event. Many meteorological and climate events result from similar combinations of more or less independent conditions. Use of joint or conditional probabilities to assess probabilities of rare events is a task not yet well dealt with and deserving of more attention.

The bottom line of this discussion is that there are as many ways of defining extreme climate events as there are investigators analyzing the problem. It is very important that we agree on a consistent definition of extreme events so that we can be assured that we are talking about the same episodes, whether we are concerned with changes in impacts or trends in natural events. This workshop would seem to be an ideal place to address such an agreement.

Historical Extremes and Trends

After major effort to generate homogeneous temperature, precipitation and wind datasets at the monthly and daily time scales, we can confidently say that we know some significant things about the variability and trends of the extremes of these climate parameters in Canada during the last 100 years. As discussed above, this can be quite different from understanding variability and trends of the extreme events most relevant to society. Some of our current knowledge about the behaviour of extremes of Canadian climate parameters during the 20th century is reported in Mekis and Hogg (1999), Zhang, Harvey et al. (2000), Zhang, Vicent et al. (2000), and Bonsal et al.

(2000) and is summarized in the following points.

- Cold season minima and maxima and minimum daily temperatures have increased but summer maxima have not. (It hasn't gotten hotter in Canada, it has gotten less cold)
- Annual accumulations and number of days with rain have increased but average intensities and number of extreme heavy rain events have not. (It hasn't rained harder, it has rained more frequently).
- Annual accumulations and number of days with snow have increased but average intensities and number of extreme heavy snow events have not.
- Globally, we have found no indisputable evidence of a systematic change in extreme winds or waves.

Important Extremes in Northern Climates

Extremes of climate parameters socially and economically important in high latitude countries like Canada consist of most of the ones important in temperate latitudes plus a few additions. High winds, intense rainfall and persistent drought conditions are universally important. In addition, intense snowstorms, extreme seasonal snow accumulations and rapid melt events (rain plus high temperatures) are critical in northern climates. Extremes indices for all of these climate parameters can be developed from simple temperature and precipitation data and examples have either been generated by Karl et al. (1996) or in Easterling et al. (1999). Severe thunderstorm conditions and associated lightning, hail, intense short duration rainfall, damaging winds and tornadoes are equally important to society but cannot be characterized by the basic temperature and precipitation datasets. The same is true for economically and socially debilitating yet complex winter phenomena like freezing rain, severe wind chill and blizzards.

Knowledge Gaps and Future Work

The signal to noise ratio is small for most time series of climate extremes. Records are rendered ambiguous by environmental changes other than climate (e.g. changing land use in river basins). Changing communication patterns change perceptions about the frequency of extreme events. Changing observing capabilities due to increasing population and use of remote sensing techniques skew statistical samples. Things like changes in monetary systems, demographics and observing systems (e.g. automation) distort comparison of even quantitative measurements. In order to understand climate extremes and their variability we must be able to objectively quantify them in the past, present and future. To do this we must choose definitions of climate extremes that are independent of the effects of the above noted factors.

The goal of future work should include the creation of systematic archives of climate extremes. This will require the definition and identification of a rational set of extreme events and will involve significant data archaeology efforts to remove artificial trends. The existence of such an archive will provide opportunities to understand the cause of climate extremes and identify the factors that contribute to variability and trend in the number and intensity of events.

Within the field of climatology some basic, practical problems need to be addressed. The tracking of climate extremes is a continental scale initiative but there are apparent discontinuities in trends of various climate parameter extremes at the Canada/U.S. border. These are caused by a combination of measurement and data interpretation differences (e.g. precipitation measurement) and these border discontinuities must be harmonized. Presumably there are similar issues at the Mexico/U.S. border which must be dealt with to ensure a consistent analysis of climate extremes throughout North America, and, by extension, more harmonization issues to permit global analyses. A joint project between Canada and the U.S. to harmonize North American climate and climate extremes databases would be a worthwhile project.

Extremes of large-area and multi-parameter events represent a class of events that require more research. For large river basins (Mississippi or Mackenzie), the duration and areal extent are as important in determining the impact of an event as is the amount of precipitation at the storm center. The organization of climate archives into station time series formats has discouraged (but not made impossible) the compilation of databases of large-area events and more emphasis must be placed on this aspect of analysis of climate extremes. Similarly, there are events that have significant impact only with the joint occurrence of special conditions in two or more parameters. Freezing rain and blizzards are examples of this category and for these and other multi-parameter events, areal extent is also a determining factor in the assessment of severity or societal impact. New approaches and statistical tools are required to document and analyze the joint probability and trends of these combination events.

Conclusion

A coordinated effort to monitor climate extremes on a continental and global basis is an important tool for monitoring climate change. But first we must agree on both the physical and impacts criteria that define a climate extreme record their historic and contemporary occurrence in systematic archives.

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Variations and Trends in Climate Extremes in the U.S.

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1. Introduction.

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

Monitoring the climate for changes is a difficult task. Often, the long-term observations available in computer-compatible form are taken from meteorological networks that usually were originally designed to observe the weather for the development of forecasts. Furthermore, the time-scale of the observations is usually monthly, seasonal, or annual averages. These types of data are useful for examining extremes such as prolonged, wide-spread droughts, or large-scale temperature anomalies (Karl et al. 1993) and developing climate indices. Short-term extreme events, such as heat or cold waves require high temporal resolution observations, such as daily maximum and minimum temperature or precipitation. Here we focus solely on temperature and precipitation with a high temporal resolution.

2. Data Problems Affecting the Analysis of Extremes

Often the analysis of extremes involves examining the tails of a statistical distribution. In other words, we are examining very high or very low temperatures, or very heavy precipitation totals or, as in the case of drought, zero values. There are a number of data problems and processing procedures that can potentially affect values in the tails of a distribution, or can affect the means and variances. In this section we discuss problems of homogeneity of the data, and quality control procedures and how these problems can affect observed extremes.

Although many problems of homogeneity may not have a large effect on the analysis of some types of extreme events there can be certain problems and certain types of extremes analyses that may have a noticeable effect. Instrument changes is one example. Record temperature observations have been known to be affected by a change in instrumentation. For example, in the U.S. First-order network the primary temperature sensor starting in the mid-1980's through to the installation of the Automated Surface Observing System (ASOS) has been the HO-83 Hygrothermometer. This is an aspirated thermistor-based system that includes both temperature and dewpoint temperature sensors. One instance where the installation of this system caused suspiciously high temperature readings was at the NWS First-order station at Tucson International Airport. A number of record high temperatures observed in the early 1990's lead to a number of studies that concluded that many of these records were likely due to inaccurate readings from the HO-83 (Gall, et al. 1992). During the 1980's nearly half of the stations in the U.S. Cooperative network had their liquid-in-glass thermometers replaced with the Maximum/Minimum Temperature System (MMTS), an unaspirated electronic temperature system. Quayle, et al. (1991) showed that, on average, the introduction of the MMTS reduced monthly maximum temperatures and increased monthly minimum temperatures, which would likely also have an affect on observed daily extremes.

Other inhomogeneities may also affect the temporal distribution of observed extremes. Station moves may cause an artificial change in observed extremes, particularly in areas of heavy terrain. Changing the siting of an instrument shelter, say from the side of a hill to the bottom, can easily cause more cold extremes to be recorded in minimum temperatures. The same can be said for extreme warm observations, if a shelter is moved from a shaded area into an area of constant sunshine.

Precipitation measurements are particularly susceptible to inhomogeneities that may affect extremes. Two main problems with precipitation measures are: (1) gauge undercatch in windy conditions, and (2) the use of gauges with different measurement mechanisms, particularly the use of tipping-bucket raingauges. Gauge undercatch is a problem with both solid and liquid precipitation (Sevruk 1982, Groisman and Easterling 1994). Wind-induced turbulence over the gauge orifice can result in much of the precipitation blowing over the gauge rather than settling into it. This is particularly a problem with snow and light rain where undercatch can be as much as 50% or more. However it can also be a problem with heavier precipitation if there are exceptionally windy conditions. One way of dealing with gauge undercatch is to install a wind shield on the gauge, which can dramatically increase the amount of precipitation caught by the gauge. However, this introduces a large discontinuity in the record that may have a large effect on the incidence of extreme precipitation events. The use of tipping-bucket raingauges also can affect the observation of extreme precipitation events. Tipping-bucket gauges are well-known to undercatch precipitation during heavy rainfall events when the rain rate exceeds the capability of the tipping mechanism to keep up with the water flowing through the gauge (Sevruk 1982).

Furthermore, the daily data often are not in digital form. Even in the United States there is a large quantity of these data for the period prior to 1948 that are only now being digitized.

3. Observed Trends.

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

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

3a. Temperature Extremes.

Relatively little work has been completed related to changes in high frequency extreme temperature events. This includes heat waves, cold waves, and number of days exceeding various temperature thresholds. Easterling (2000) examined trends in the number of days in the U.S. exceeding thresholds of 0C, 32.2C (90F), and thresholds derived using non-parametric statistics (percentiles). Trends indicate that for the 1910-1998 period, there has been a slight decrease in the number of days below freezing over the entire U.S. Trends in the number of days with the maximum temperature over both 32.2C and the 90th percentile threshold are dominated by large anomalies partially due to the very dry land surface conditions during the droughts of the 1930s and 1950s. Overall there is a slight downward trend in the number of these extremes despite an overall warming in the mean temperature, but with cooling in the Southeastern U.S. (Karl et al. 1996). Two studies focused on the Northeastern U.S. support the notion that changes in the number of days exceeding thresholds have occurred. Cooter and LeDuc (1995) show that the start of the frost-free season in the Northeastern U.S. occurs 11 days earlier now than in the 1950s. In an analysis of 22 stations in the Northeastern U.S. for the 1948-1993 period, DeGaetano (1995) found significant trends to fewer extreme cold days, and also trends to fewer warm maximum temperatures as well.

Apparent temperature, which combines temperature and humidity effects on the human body is another important measure, particularly for human health. Gaffen and Ross (1998) show regional summertime increases in days exceeding 85th percentile threshold value for apparent temperature in the U.S. This result would appear to be in contrast to trends found by Easterling (1999) for the 1910-1998 period. However the period used by Gaffen and Ross was 1948-1997, which would exclude the effects of the 1930s droughts on extreme high temperatures and could at least partially account for the trend differences.

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

3b. Precipitation.

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

3c. Drought and Wet Periods.

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

Although there appear to be no long-term trends in drought, the area of the U.S. experiencing excessive wetness appears to be increasing, particularly since the 1970s (Karl et al. 1996). This is consistent with long-term increases in annual precipitation, and increases in heavy precipitation events discussed previously.

3d. Tropical Storms.

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

Hurricane impacts are not restricted to the Southeastern U.S. Recent work has documented the contribution of hurricanes to very extreme rainfall events (the individual event results in double the monthly rainfall being measured in that month) in the mid-Atlantic and New England regions of the USA (Evans and Hart 1999). For the 67 year period studied, eastern Massachusetts and much of the Appalachians experience such extreme rainfall events on average every 5-6 years, and the return period drops to 2-4 years when hurricane rainfall contributions result in monthly rainfall anomalies of 150% above average.

4. Indices of Climate Extremes.

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

5. Summary.

There is still much work to be done in determining whether significant large-scale changes in these types of events are occurring in the U.S. and around the globe. One of the biggest problems in performing analyses of extreme climate events for most of the globe and even in the U.S. is a lack of access to high-quality, long-term climate data with the time resolution appropriate for analyzing extreme events. International data exchange is becoming increasingly difficult as countries develop cost recovery programs for access to climate data. Furthermore, much high temporal resolution data remains undigitized throughout the world. More support for programs such as the World Meteorological Organization's Data Rescue Project is needed. Homogeneity of data is also a problem, particularly in examining extremes such as exceeding a specific threshold. Observations of extremes such as thunderstorms and tornadoes often have biases due to such factors as increased population density. For example, the increase in tornado observations in the United States in this century is likely due as much to the fact that more people live in tornado prone areas and are able to report tornado occurrences that otherwise would have gone unreported, as any real increase. To address these types of homogeneity and biasing problems, one approach is to use a surrogate for extreme weather such as examining long-term variability and trends in atmospheric conditions known to be conducive to severe weather. Lastly, it is critical that monitoring efforts, such as the Global Climate Observing System (GCOS), receive enhanced support. Without such efforts our ability to detect long-term variability and trends in extreme climate events will remain hampered.

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Projected changes in annual extremes under equilibrium and transient climate change

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1 Introduction

This note[1] briefly describes changes in climatic extremes that are projected with the current generation Canadian climate model for the middle and end of the 21st century. This climate model has been used extensively in the U.S. National Assessment of the Potential Consequences of Climate Variability and Change (http://www.nacc.usgcrp.gov). Output from the model is freely available from a number of sources, including the web site of the Canadian Centre for Climate Modeling and Analysis (CCCma; http://www.cccma.bc.ec.gc.ca) and the Data Distribution Centre of the Intergovernmental Panel on Climate Change (http://ipcc-ddc.cru.uea.ac.uk/). Unfortunately, it is beyond the scope of this short note to provide a comprehensive overview of the ability of models to simulate extremes. Also, we do not consider the consequences of climate change on the dynamical extremes of climate (winds, mid-latitude storms, hurricanes, etc.). See however, Meehl et al. (2000) for a recent review of model based research on climatic extremes.

We briefly describe here changes in annual extremes surface properties (2-meter screen temperature and precipitation) simulated in an equilibrium climate change simulation and an ensemble of 3 transient climate change simulations performed with CCC GCM2. The equilibrium change experiment (Boer et al., 1992) was performed with a version of GCM2 that is coupled to a mixed layer ocean model (McFarlane et al., 1992). The transient change experiments for 1850-2100 (Boer et al., 2000a, b) were performed with a version of GCM2 that is coupled to a modified version of the GFDL Modular Ocean Model and a thermodynamic

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[1] This note is an update of Zwiers and Kharin (1999).

sea-ice model (Flato et al., 2M). The effective C02 and aerosol forcing prescription used in these transient simulations is described by Mitchell et al. (1995). The manner in which the direct aerosol effect is implemented in the model is described in Reader and Boer (1998). Further details on the model and output from both experiments are available from the CCCma, web site (http: //www. cccma . bc. ec. gc. ca). A detailed description of the changes in extremes in the equilibrium experiment is given by Zwiers and Kharin (1998; here after "ZK"). Kharin and Zwiers (2000) (here after "KZ") describe the changes in the transient simulations.

2 Extreme value analysis methodology

Extreme value analyses, were conducted with samples of annual extremes of screen temperature minima and maxima, annual maximum 24-hour precipitation amounts. Analyses have also been performed on annual maximum 1000 hPa wind speed, but these are not discussed here (see ZK and XZ for details). Samples of 20 annual extremes were obtained from the control and doubled C02 runs that comprise the equilibrium change experiment. Samples of 63 annual extremes were extracted from the transient experiments for each of three 21-year windows representing 1975-1995, 2040-2060 and 2080-2100.[2] Temperature and precipitation extremes were derived at run time by sampling these fields at every time-step of the simulations. Wind speed extremes, on the other hand, were derived from values archived at 12-hour intervals.

A statistical extreme value analysis technique (see, for example, von Storch and Zwiers, 1999, for a brief introduction) was used to estimate the long period *return values* of the extremes simulated by the climate model. The so-called generalized extreme value (GEV) distribution was fitted to the annual extremes at each model grid point using the method of L-mornents (Hosking, 1990). Return values were estimated for various return periods. A bootstrapping method (see von Storch and Zwiers, 1999) was used to determine the uncertainty of the derived estimates. Because the greenhouse-gas signal is small in precipitation and wind-speed, an attempt was made to use a spatial smoothing approach to decrease the uncertainty of estimated changes in return values under equilibrium and transient climate change. This worked well for precipitation

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[2] Each member of the ensemble of three simulations provides a sample of 21 annual extremes for each of the time windows, so that there is a combined sample of 63 annual extremes for each.

because its variations are not strongly coherent spatially. However, we were not able to reduce the uncertainty of the estimated changes in wind speed extremes with this technique. Methodological details are given in ZK and KZ describes further refinements.

3 Extremes in the equilibrium control climate

The validation of extremes simulated by climate models is difficult on a global scale because reliable gridded observed data comparable to that produced by the model is scarce. We therefore limited our comparison on the global scale primarily to NCEP-NCAR reanalysis data for 1979-95 (Kalnay et al., 1996) and ECMWF reanalysis data for 1979-93 (Gibson et al., 1997). We also compared simulated extremes over Canada with estimates derived from Canadian temperature data (about 160 stations with an average record of about 50 years) and precipitation data (approximately 500 stations with an average record of about 25 years; Hogg and Carr, 1985).

3.1 Screen Temperature

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

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

3.2 Precipitation

Return values in the tropics and sub-tropics in the model reflect the large-scale divergent tropical circulations of the simulated climate. The locations of the upward (high return values) and downward (low return values) branches of these circulations are easily discernible. The very large simulated return values (more than 200 mm/day) in the western tropical Pacific are likely overestimated since CCC GCM2 simulates more precipitation in the Asian summer monsoon outflow area than is observed. Various other differences are also seen in the tropics. The model does a credible job of simulating precipitation extremes at mid latitudes, but twenty year extremes are somewhat too large at high Northern and Southern latitudes. This problem has been corrected in the latest version of the CCC GCM.

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

4 Changes under equilibrium climate change

4.1 Screen Temperature

The equilibrium change under *C02* doubling in the estimated 20-year return values of the daily Minimum and Maximum temperature, *T min,20* and *T max,20* respectively, are not equal. For example, the global mean change for *T max,20* is 3.14 degrees C., whereas that for *T min,20* is 5.O degrees C.

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

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

Increases in T min,20 over North America and Western Asia are larger than the corresponding increases in T max,,20. This presumably occurs because snow cover is reduced in the warmer world. Increases in T min,20 over Siberia (which remains snow covered in winter under C02 doubling) are roughly comparable to the increases in T max,20. Changes in both quantities are also roughly comparable over Africa. Over South America however, increases in *T Min,20* are smaller than those in *T max,20,* perhaps because of a decrease in soil moisture and clouds.

Only small increases in T Max,20 occur in polar regions which retain some sea ice. Presumably temperature maxima are strongly constrained here by the cold water which is exposed as leads and thus contains melting ice. For the same reasons (increased leads and thinning of the sea ice) large increases are observed in *T min,20.* This occurs because the atmosphere is in better contact with the ocean in the 2XC02 climate.

4.2 Precipitation

Smoothed estimates of the change in the 20-year return values of 24-hour precipitation are positive almost everywhere.[3] The largest increases, over 50 mm/day, are found over the northwest coast of India where there is intensification of the Asian summer monsoon under C02 doubling. Globally averaged, 20-year return values increase 9 mm/day (11%) while the daily mean rate increases by only 4% (0.11 mm/day). Over Canada, 20-year return values increase approximately 7 mm/day (14%) which translates into a 50% reduction in the mean waiting time between 1 *X* C02 extreme events in the 2 *X* C02 world. ZK provides more detail, including an analysis of the change in intensity and frequency of precipitation in the warmer world.

5 Changes under transient climate change

A similar approach was used to estimate changes in the extremes temperature and precipitation in the transient climate change simulations at the time of C02 doubling relative to the present (i.e., 2040-2060 vs. 1975-1995) and at the time of tripling (2080-2100 vs. 1975-1995). Globally averaged changes in the means and the 20-year return values at the time of doubling and tripling in the transient experiment, and also in the equilibrium experiment, show that changes at the time of doubling are relatively modest when compared with those for the equilibrium experiment.

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[3] The smoothing technique used is described in ZK.

5.1 Temperature

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

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

As in the equilibrium change experiment, the changes in the return values of daily minimum temperature are larger than those of daily maximum temperature over land areas and high latitude oceans where snow and ice retreat. In a global sense, minimum temperature extremes at the time of tripling are comparable to those under C02 doubling in the equilibrium experiment. However, somewhat larger changes are found over land masses and the Arctic while smaller increases in extreme minimum temperatures occur at the margins of the polar oceans.

5.2 Precipitation

Globally averaged, there is little change in the annual mean amount of precipitation at the time of doubling and only a modest increase at the time Of C02 tripling. However, there are substantial shifts in the spatial distribution of precipitation that are associated with a warming pattern that is reminiscent of a gradually strengthening permanent El-Nino. This is a common, but not ubiquitous, response of coupled climate models to transient greenhouse gas forcing.

There are associated increases in extreme precipitation almost everywhere (Figure 4). The largest increase in 20-year return values occurs in the tropical Pacific. While changes of less than 10mm are evident over extra-tropical land masses at the time of doubling, large areas, including eastern North America, are affected by substantially larger increases in the size of these extremes at the time of tripling.

6 Summary

We have briefly described an extreme value analysis of equilibrium and transient change experiments performed with CCC GCM2, and its coupled version which is known as CGCMl. A limited comparison with Canadian observations and NCEP/NCAR and ECMWF reanalysis data suggest that the model simulated extremes bear at least some resemblance to those of the real world. There are relatively small differences in extreme temperature changes simulated in the equilibrium and transient runs that are associated with differences in the response of the ocean and sea-ice to the forcing changes. There are relatively larger differences in the extreme precipitation changes simulated in the two experiments which are associated with differences in the mean temperature response, particularly in the tropical Pacific. An effort is underway to intercompare extremes simulated by a number of the models participating in the second Atmospheric Model Intercomparison Project (AMIP2; see **http://www-pcmdi.llnl.gov/amip/amiphome.html** and **http: //www-pcmdi. 11n1. gov/amip/DIAGSUBS/sp 18. html).**

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Advances in Climate Modeling

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1. What are the current capabilities of climate modelers to provide the output required by the impacts modeling community?

Readily available model outputs are the free-atmosphere prognostic state-variables such as temperature, wind and moisture plus certain diagnostic variables such as precipitation and radiation. Also available are certain boundary layer (BL) variables including the fluxes of heat, moisture, momentum, radiation, soil moisture, snow cover, snow depth, ice cover fraction over water, etc. but these are all for the *model's* BL not the real BL. All of this is available at the *model's* spatial resolution (100s of km for global models, 10s of km regional models). In the model, surface characteristics such as elevation, roughness, vegetation, soil moisture, open water fraction, etc., etc. are represented as smoothed values appropriate to the *model's* resolution. Clearly this has a profound effect on the model's atmospheric BL variables themselves, so these variables must be used with caution. They *cannot* be treated in the same way as observed values. The time resolution available is, in theory, excellent since the model resolution is in the order of tens of minutes. In practice almost no modeling group archives information every time-step. Instead they archive daily averages, maxima and minima and samples every 6, 12 or 24 hours depending on the variable. Variances, probability of extremes, return periods, etc. can be calculated from these sampled values but the effect of the sampling frequency must be accounted for.

2. What are the uncertainties associated with current projections of extreme events and what are the limiting factors (e.g. temporal and spatial scales)?

Model internal space and time variability is not the same as real variability. It is usually less, because of lack of small space- and time-scales. Time truncation errors are usually less serious than space truncation errors but model output is usually sampled at much less than once per time step, which introduces sampling errors. That part of the variability that is forced by small-scale topography and land/water contrast is lacking, or at least underrepresented, depending on model resolution. Nevertheless the calculated *changes* in the large-scale variability due to climate forcing may be OK for some variables. To the extent that the lack of small scales affects the larger scales, even the large-scale changes in variability may not be correct. There is some evidence that the large-scale changes computed by regional models are not always the same as the changes *on the same scale* computed by global models. This is almost certainly the case in regions of prominent or complicated topography for variables such as precipitation. This may mean that the downscaling problem may be easily solved for temperature by the so-called delta method but may require the further development of regional scale models for precipitation.

The full analysis of extremes requires access to raw model data, which means that only those closely connected to a modeling group can do it. A full analysis has not done yet for most models; this work is really just beginning. There are questions of statistical significance that can be partly resolved by running larger ensembles of integrations. Uncertainty is inherently greater (statistical significance lower) for highly variable quantities such as moisture, precipitation and wind.

3. What improvements do climate modelers expect to make in the future?

Resolution will slowly improve, at roughly a factor of two per decade. The representation of resolved physical processes and parameterization of unresolved processes is slowly improving. Improvements are in the works for ocean eddy transports, ocean boundary layer and shelf processes and improved representation of sea-ice. Better representation of land surface processes, including soil moisture, run-off, lakes, wetlands and the ice phase on land (snow, ice sheets, permafrost) is also coming. Improved treatment of clouds, aerosols and radiation are slowly being introduced The addition of tropospheric chemistry, wet and dry is coming as well as stratospheric and mesospheric processes, transports, chemistry, radiation, etc. Later will come the addition of an interactive carbon cycle (CO2, methane), first for land, involving a calculation of the storage and release of carbon from vegetation, soils, wetlands and permafrost, and later for oceans.

4. Are there things that the impacts community requires that climate modelers believe cannot ever be provided (owing to the complexity of the climate system)?

Complexity (in the sense of non-linearity and chaotic behavior) is not really an issue in the sense that non-linearity is precisely the reason for developing large complicated climate system models because the only way to deal with non-linear processes is to attempt to simulate them in detail in a computer. Progress will continue to be made in separating the signal (response to forcing) from the noise (natural variability). Although absolute certainty will never be possible, confidence limits can be expected to slowly narrow. Don't look for extremes of the type associated with severe convective phenomena such as tornadoes or even hurricanes until models have sufficient resolution to represent them properly. Global models are beginning to represent hurricane scales. Some progress is being made in defining "catastrophe thresholds" which if exceeded might cause the climate system to flip into a rather different mode of operation but a confident understanding is still a long way off.

5. What computational advances (physics, resolution, program structure) are required to address the identified needs of impacts and climate community?

The impacts community, like everyone else, needs climate predictions based on models that better simulate past and current climate and hence produce more confident projections of future climate. This means continued refinement of models along the lines noted above. Resolution is still far from sufficient. Additional resolution will require modification of algorithms for processes that are currently parameterized as the higher resolution allows them to be explicitly represented. The eddies that do most of the work of transport in the atmosphere are reasonably well represented, but not so in the ocean. Better parameterization of ocean eddies will continue to be needed. It will simply not be feasible to build ocean eddy resolving models without major increases in computational power.

6. What are the critical issues in climate modeling to project extremes that should/could be tackled within the next 3,5 and 10 years? What recommendations do you have for addressing these issues?

One of the first things to do is to better define extremes for the current climate. We need to arrest the decay in the global climate observing system, generate high resolution standard climatologies, complete the clean-up of archived observations and the analysis for those extremes which are deemed critical for climate impacts. This will form a basis for judging modeled extremes, without which we can have no confidence in projections. This work would proceed much faster if the cleaned up historical data were more readily available to researchers.

For modeling the changes in climate extremes there is a need to define a greater range of standard forcing scenarios and to generate larger ensembles of integrations based on them, in order to explore the range of possible outcomes and to better understand model dependence. The frequency distributions of model variables need to be compared with those calculated from observations. Analysis should focus on those extremes that are known to be critical to impacts. This will require close interaction between the modeling and impacts communities. These analyses will have to be repeated for each new generation of models with higher resolution and more complete representation of physical processes.

Advances in Impacts and Vulnerability Modeling

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Introduction

The following presentation attempts (1) to outline some of the questions most relevant to assessing the human environment's vulnerability to the impacts of weather extremes, especially in the context of global climate change; (2) to highlight some of the needs, uncertainties, capabilities, and insights of the two communities -- weather/climate modelers and operations/policy managers -- most involved in discussing these questions today; and (3) to provide some suggestions for the guidance of both communities as they map out their research agenda for the next three, five, and ten years. And of course I acknowledge freely that all these suggestions and insights have been developed over time in conversations with many colleagues, and through a selective reading of their papers and presentations. In particular, I should mention that my conclusions here owe much to Stan Changon's presentation at Aspen last year.

What are the capabilities of impacts and vulnerability modeling to replicate current conditions? And to simulate future conditions

- There are a variety of analytical methods that can be used for climate impacts and vulnerability assessments. These range from qualitative descriptive studies, through more diagnostic and semi-quantitative assessments to quantitative and prognostic analyses.
- the study of climate change impact assessment has, during the last two decades, evolved from primarily simple expert judgment to simulations of numerous components and processes of the Earth system.
- The majority of the applications, however, focus on scenario analysis. As scenarios on changes in extreme are not available, applications which take account of extreme events are relatively rare.
- Traditional impacts and vulnerability assessment approaches

focus either on physical, biological, or economic aspects of the earth system. Except in the case of integrated assessment, they often deal with one economic sector in isolation. These methods have limited capabilities to study discrete (temporal and spatially limited), outside the normal events rather than routine and continuous or gradually changing conditions

- Current research directions suggest that to study impacts and vulnerability of extreme events, it is necessary to develop more sophisticated tools that can deal with uncertainty and risks
- In terms of current capabilities, it appears that the furthest along in replicating impacts and vulnerability is in the area of water resource management, although this capability is basin specific. The existing models appear to replicate current conditions “well”, however, the challenge is to produce similar capabilities for other major watersheds. Another concern is broadening the capabilities to include other interacting basins. For example, capabilities with respect to modeling in the Great Lakes are relatively good, but even here there are gaps between capabilities within the Great Lakes, integrating these with the Ottawa, the St. Lawrence, and the Gulf of St. Lawrence and although progress on the Prairie pothole wetlands, little effort is underway within the Great Lakes.
- operational hydrologic models or at least real-time monitoring systems are in place in many urban watersheds in southern Canada - run by provincial or local authorities and used to issue flood advisories and warnings.
- The Grand River Conservation Authority has developed a damage model to estimate the impact of various flood stages on the watershed. They have used it in combination with their hydrologic models to estimate the impact of a “Saguenay event” if it were centred over the Grand River Basin.
- Many large urban municipalities have pseudo-operational water demand models that include weather variables. Coupled with a good water storage monitoring system, they enable water managers to issue lawn watering restrictions, etc. These are most often used when expansion of the water supply/distribution and wastewater systems are being considered. Contractors use such models to develop base and peak demands that ultimately become design criteria or set objectives for water conservation programs. The demand models include things like pricing, population/demographics,

industrial mix, water conservation programs, etc. and could be used to examine vulnerability to drought.

- the University of Washington has developed a model for the Columbia Basin system that incorporates both hydrologic impacts and the management system of various dams and reservoirs
- Other sectors employ operational models and data monitoring systems that could be adapted for use in longer-term climate sensitivity studies
- Through remote sensing analysis, road sensitivities to frost, drifting snow, etc. can be identified. The accumulated data through these types of monitoring and analysis programs could be used to develop a "road weather climatology" that in turn could be combined with road descriptors (e.g., traffic volume, road construction/surface, etc.) and accident statistics in a vulnerability analysis.
- Agricultural and forestry models also exist with varying degrees of sophistication, from single crop/plot models to full continental and global models. These can be used to understand impacts and vulnerabilities of the current climate, however, implications in terms of capabilities to address impacts of extremes are limited - some site specific models associated with windfall and capabilities with respect to forest fire severity and drought are available.
- The models, however, do not always behave as expected with the weather/climate inputs. It is not clear what is at fault, the limitations of the weather/climate data to provide the model with the required input at the scale needed by the model or the limitations of the models themselves.
- Severe weather "box" and weather typing analysis approaches exist that could be used for climate impacts assessments: these fairly well established meteorological techniques for mapping overlapping zones of vulnerability could be usefully applied to understanding complex/composite events.

What are the uncertainties associated with these types of models and what are the limiting factors?

- There are three major limiting factors that contribute to the uncertainties of impacts and vulnerability models for extreme events - scenario, response, and model uncertainty:
- The lack of quantifiable observations and future scenarios (scenario uncertainty) for extreme weather and climate events;
- sources include descriptive errors (time and magnitude of the change), down and up scaling errors (associated with

assumptions of the homogeneity of changes and socio-economic conditions and spatial and temporal approximations), and incomplete analyses (lack or unquantifiable information

- Inability to characterize the inherent variability in environmental and socio-economic parameters (parameter uncertainty);
- climate and system conditions vary significantly at any given location and human activity pattern and social and cultural values can differ substantially over the next century (the further you go from the present the greater the likelihood that these parameters will change, which raises questions about the findings of models based on present climate-society relationships
- most approaches for characterizing these types of uncertainties have focused on techniques that examine how uncertainty in parameter values translate into overall uncertainty in the assessment - include sensitivity analyses, analytical uncertainty propagation, probabilistic uncertainty analyses, and classical statistical methods
- Gaps in scientific theory required to make predictions on the basis of causal inferences (model uncertainty).
- due to models being simplified representations of reality
- capabilities of impacts and vulnerability models are limited by the characteristics of the climate and system data on which they are based. The accuracy and precision of these data and temporal and spatial scales at which a model is to be representative are determining factors - any uncertainties that are inherent in the inputs will be transferred to the impact model
- only partial validation is possible due to data deficiencies or model complexities
- even when validated under a particular set of conditions, uncertainty will exist in applications to other situations
- Combining information from different sources with different characteristics and quality (e.g., climate models, socio-economic projections/scenarios, ecosystem dynamics) can contribute to uncertainties in impacts and vulnerability assessments
- Capabilities with respect to integrating knowledge from the research communities with that of stakeholders and practitioners towards enhancing impacts and vulnerability modeling capabilities

What sort of output from climate models would be most useful if it were available?

- A lot can be done with synoptic descriptors in addition to the more traditional climate variables and their statistics such as temperature, precipitation amount and type, and radiation. Wind speed and direction would also have some value in the context of extremes.
- There is believed to be considerable valuable (user/stakeholder defined) information within current GCMs despite the perception of limitations of spatial and temporal resolution and there would be considerable "value" in extracting this information - the key is identifying and defining what information has value to the operations and impacts research communities.
- Many of the variables currently available are useful - but the impacts community has not put sufficient time into examining their utility and limitations.
- It would be helpful to develop extreme event scenarios (include changes in variance) based on GCM and RCM outputs that would allow one to identify the probability or potential frequency of extreme events (droughts, floods, severe sub-synoptic scale storms, and severe synoptic scale extra-tropical storms and tropical storms)
- development of scenarios of extreme events - current methodologies for precipitation, for example, apply ratios of changes to existing time series of climate station precipitation data - cannot change the intervals between precipitation events, the intensity or duration.
- at present, climate scenarios are not able to indicated whether the frequency, intensity, duration and extent of extreme climate events will vary significantly in a doubled carbon dioxide environment. Such research objectives could provide valuable and manageable guidance on the track, frequency and the intensity of meteorological systems of interest
- In terms of extremes within GCMs, it is believed that it is difficult to say anything with certainty about specific localities, but it should be possible to learn something about extremes in the simulated climate and how they change - generic clues about how extremes might change in future. Possible directions include developing information on:
- the causal mechanisms for historical extreme events of the past century: we want to be able to relate these to mechanisms that could be identified within GCMs. This could include

information on climate extremes (e.g., occurrence, intensity and return period) such as relationships between the characteristics of the baroclinic zone (i.e. storm tracks, intensity) and the occurrence of extremes; and

- the accuracies of GCM simulations of current climate with respect to the occurrences of synoptic scale features often associated with extreme events (e.g. the infrequent high amplitude wave activity responsible for some of the major extreme precipitation episodes)
- All this being said, I would suggest that there are more significant limitations with bio-physical and socio-economic data collection, quality control, standardization and future scenario development
- need to document and make available information on the impacts of extreme events.

What are the critical issues in impacts and vulnerability modeling that should/could be tackled within the next 3, 5, and 10 years? What recommendations do you have for addressing these issues?

- Incorporation of operational knowledge into a modeling framework.
- A tremendous amount of expertise exists only in the minds and experiences of managers of systems threatened by extremes. When the research communities go in, they need to learn the system, model it , and make some estimates. This process is much improved when we gain the trust of the operational communities and obtain critical (albeit often qualitative) information about the unique qualities of their systems. An ideal mix would combine "bottom-up" with "top-down" methods of understanding vulnerability.
- Such model-aided, mutually informing dialogue with managers and other users/stakeholders can be a useful approach. If tools can be constructed that enable climate change to be assessed in an explicit way, then we can have a dialogue that looks at the regional dimensions of a global scale problem
- there is a lot that could be done given an appropriate level of time, resources and coordination.
- inadequate data access and poor climate monitoring practices are two primary issues that must be improved if we expect to make much progress in this area. For example, climate monitoring can no longer be relegated to weather operations; the scientific basis, rationale and oversight for long-term monitoring of climate and weather extremes must be given high

priority.

- analyses of variability as well as mean trends would be simple yet enormously useful for applications, especially if conducted in a manner where the temporal and spatial scales matches that of decision makers (e.g., water basins, ecological zones)
- Since climate extremes such as droughts and temperature anomalies can be defined as large areas experiencing unusual climate values over longer periods of time, one way to investigate trends in climate extremes over time is to develop indices that combine a number of these types of measures.

Conclusion

- The major difficulties in adapting to weather and climate shifts will come from changes in the variability and extremes of the climate, not from shifts in the mean or average conditions
- Greater certainty than exists now over future changes of climate and its magnitude and structure, such as extremes, could lead to major savings in infrastructure replacement and designs of weather-sensitive systems to gain greater future flexibility. Greater flexibility in weather-sensitive sectors is good business, particularly recognizing that the climate of the next 50 to 100 years will be different, regardless of the cause, than the climate of the past 50 to 100 years. Hopefully, greater understanding amongst decision makers will lead to the planning and expenditures to attain greater flexibility in weather sensitive systems

CLIMATE CHANGE AND HEALTH: NEW RESEARCH CHALLENGES

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According to the United Nations Intergovernmental Panel on Climate Change (IPCC), anthropogenic greenhouse gas emissions are significantly accelerating current global surface warming trends and are inconsistent with natural climate variation. [1] This century the earth has warmed by about 0.5˚C, and the mid-range estimates of future temperature change and sea level rise are 2.0˚C and 49cm by the year 2100, respectively. [1] If such changes occur, diseases that are influenced by weather factors could be expected to respond to an altered climate regime.

The commonly used term "global warming" is inadequate to describe the range of climate effects of greenhouse gas accumulation. In addition to concerns about temperature and sea level rise, climatologists, ecologists, and health and other scientists are concerned that accelerated evaporation will drive a more extreme hydrological cycle, producing more frequent or severe floods and droughts. The regional impacts of these climate changes will vary widely depending on existing population vulnerability.

Extreme weather variability associated with climate change may add an important new stress to developing nations that are already vulnerable as a result of environmental degradation, resource depletion, overpopulation, or location (e.g., low-lying coastal deltas). Persistent poverty, accompanied by inadequate sanitation and public health infrastructure, will also limit many populations' capacity to adapt to this newly recognized environmental risk factor.

The broad spectrum of multisectorial impacts posed by climate change illustrates the need for truly multidisciplinary research and integrated assessments that address the range of regional climate and health effects. This paper reviews major climate-sensitive health outcomes, many of which are currently being studied by our program and collaborating institutions.

OVERVIEW OF HEALTH IMPACTS OF CLIMATE CHANGE

There are three well-recognized physical consequences of climate change: 1) temperature rise; 2) sea level rise; and 3) extremes in the hydrologic cycle. A recent paper in the journal Nature [2] presented a fourth complication, accelerated ozone depletion, which results from the trapping of heat in the troposphere, thereby cooling the stratosphere. These four physical attributes of climate change are expected to: increase the frequency of heat waves and potentially air pollution episodes; increase the number of extreme weather events; cause coastal flooding and salination of fresh water aquifers; and (if ozone depletion is exacerbated) increase ultraviolet radiation exposure.

Seasonality in disease incidence can often imply an association with weather factors. In sub-Saharan Africa, epidemics of meningococcal meningitis consistently erupt during the hot dry season and subside soon after the onset of the rainy season.[3] In the southwest US, rodent-borne Hantavirus has been linked to El Niño driven flooding leading to an upsurge in mouse populations. [4] In Peru, prevalence of the diarrheal disease, Cyclospora, peaks in summer and wanes during cooler winter months. [5] The current extent of our understanding of climate/disease relationships varies considerably, as discussed in more depth for other examples below.

Heat-related Illness: While the relationship between ambient temperatures and seasonal variability in mortality rates has been extensively studied, this expected direct health consequence of climate change is far from resolved. Cardiovascular mortality in the elderly comprises the largest number of heat-related fatalities; however, physiological responses to both extreme heat and cold are not straightforward. For example, blood viscosity and cholesterol have been found to increase with high temperatures, [6] whereas blood pressure and fibrinogen levels increase during winter (although outdoor temperature does not seem to determine the seasonal variation of fibrinogen). [7] In some cases, rainfall and snowfall have been found to influence winter mortality more than temperature, further complicating the health assessment of future winters that may be warmer but wetter.

Mortality curves assume a classic J or V-shape, with highest mortality occurring at both temperature extremes. Generally, populations in warmer regions tend to be most vulnerable to cold,[8] and those residing in cold climates are most sensitive to heat.[9] In temperate regions, mortality rates are highest during the winter.

The Chicago heat wave of July 1995 led to over 700 excess deaths in the metropolitan area. Climatologists project a doubling in the frequency of heat waves associated with a rise of 2-3˚C in average summer temperature. A study of 44 U.S. cities found that, after adjusting for some expected acclimatization, heat-related mortality could increase by 70-150%.[9] A meta-analysis of 20 international cities, however, found a reduction in mortality due to fewer deaths during winter. In short, there is a need for more extensive net annual mortality estimates stratified by season, cause of death and other main confounders.

Air Pollution: Increased ambient temperature and altered wind and air mass patterns can affect atmospheric chemistry and, thereby, air pollution. For example, there is a nonlinear relationship between temperature and the formation of ground level ozone (photochemical urban smog): above 90˚ F there is a strong positive relationship with temperature. The relatively high ozone levels in the U.S. during 1988 and 1995 were likely due in part to the hot, dry, stagnant conditions.

With increasing demand for automobiles, ozone is a growing problem in the developing world and continues to be the most pervasive air pollution problem in the U.S., with an estimated 71 million people living in counties that exceeded the National Ambient Air Quality Standards (NAAQS) in 1995[11]. Ozone is a potent lung irritant and can heighten the sensitivity of asthmatics to allergens. An increased frequency of heat waves could be expected to worsen ozone problems in urban areas. One study that held emissions and other weather factors constant showed that a 4˚C warming could: 1) increase maximum ozone concentration by about 20% and double the area out of compliance with the ozone NAAQS in the San Francisco Bay area; and 2) nearly triple the areas exceeding national standards in the U.S. Midwest and Southeast.[12]

Malaria and other Vector-borne Diseases: Malaria is believed to be the most climate-sensitive vector-borne disease and thus most sensitive to climate change.[13] There are 300-500 million new cases of malaria annually, with an estimated 2 million annual malaria fatalities, the majority being young children. Infectious disease agents that must cycle through cold-blooded insect "vectors" to complete their development are quite sensitive to subtle climate variations. [14]

The minimum temperature for parasite development of *Plasmodium falciparum* and *P. vivax* approximates 18˚C and 15˚C, respectively. In the typically non-endemic highlands of Kenya, [15] Rwanda [16], and Zimbabwe [17] increases in ambient temperature have been linked to malaria epidemics. Also, the incidence and prevalence of malaria is closely associated with altitude, [18] a good proxy for temperature. One scenario-based climate change/malaria modeling study concludes that the global population living within a potential malaria transmission zone could increase from 45% to 60% by the year 2100. [19]

While malaria tends to be seasonal, there is substantial interannual heterogeneity of malaria incidence around the globe. [20] Extremes of rainfall (both drought and floods) associated with El Niño events have been linked to variability in malaria incidence in some regions. [21,22] But the link between El Niño frequency and future climate change is still uncertain.

Other climate-sensitive diseases include mosquito-borne arboviruses, such as encephalitis, dengue fever, and Ross River virus. Field and lab studies on St. Louis encephalitis, [23] as well as lab studies on dengue virus, indicate that higher temperatures hasten viral development (or extrinsic incubation period, EIP) inside the mosquito. [24] Human outbreaks of Saint Louis encephalitis are highly correlated with several-day periods when temperature exceeds 85˚F. [25] Ross River virus, causing epidemic polyarthritis in Australia, shows a positive association with increases in minimum temperatures and rainfall. [26]

Disease dynamics and insect ecology are complex. For example, higher temperatures also reduce adult mosquito survival. However, since minimum temperatures are expected to rise disproportionately compared to maximum temperatures, pathogen EIP may rise faster than adult survival declines. Climate change modeling studies of dengue fever using a vectorial capacity model (which combines variables including mosquito survival, EIP, biting rates and others) have found increases in the potential transmission of dengue due to climate change. [27,28] Yet actual risk, as opposed to potential global or regional risk, will depend on site-specific factors; fully parameterized climate-driven models have successfully predicted dengue risk as validated against historical data in some locations. [29]

Water-borne Diseases: In 1995, 3.1 million people died from diarrheal diseases, 80% of them children. [30] Extremes of the hydrologic cycle could worsen the problem since both water shortages and flooding are associated with diarrheal diseases. In developing countries, water shortages cause disease through poor hygiene. On the other extreme, flooding can contaminate drinking water from watershed runoff or sewage overflow. Since 1900, many regions of the U.S. have experienced an increased intensity of precipitation (e.g., more frequent heavy downpours), and the trend is expected to strengthen due to climate change. [31]

Cryptosporidiosis, a zoonotic disease associated with domestic livestock, may be affected by altered weather patterns. Floods, storms, heavy rainfall and snow melt wash material of fecal origin into surface drinking water sources, and the oocyst is resistant to chlorine treatment. The Milwaukee outbreak in 1993, which resulted in 403,000 reported cases, coincided with unusually heavy spring rains and runoff from melting snow. Preliminary research results from our program show that the majority of historical water-borne outbreaks in the U.S. (involving multiple agents) are preceded by heavy rainfall events.

In the marine environment, warm water and nitrogen favors blooms of dinoflagellates that cause red tides which can cause paralytic shell fish poisoning, diarrheic shellfish poisoning, and amnesiac shellfish poisoning. During the 1987 El Niño a red tide of *Gymnodinium breve*, previously confined to the Gulf of Mexico, extended northward after warm gulf stream water extended far up the East coast resulting in human neurological shellfish poisonings and substantial fishkills.[32] Similarly that year, an outbreak of amnesic shellfish poisoning occurred on Prince Edward Island when warm eddies of the Gulf Stream neared the shore and heavy rains increased nutrient rich runoff.

Copepods (or zooplankton), which feed on algae, can serve as reservoirs for *Vibrio cholerae* and other enteric pathogens. In Bangladesh, cholera follows seasonal warming of sea surface temperature that can enhance plankton blooms. [33] The Peruvian outbreak in 1991 coincided with an El Niño event and satellite images of sea surface temperature confirm a close temporal relationship between the arrival of warmer waters along the Peruvian coast with the epidemic starting soon afterwards; simultaneous initial coastal outbreaks that occurred hundreds of kilometers apart imply a marine environmental reservoir (likely zooplankton), and this hypothesis is under epidemiologic investigation.

Water Resources and Agriculture: Several factors come into play when predicting the impact of climate change upon crop and livestock production. First are the direct effects of temperature, precipitation, CO_2 levels (e.g., the CO_2 fertilization effect) and extreme climate variability and sea level rise. [34] Next are the indirect effects of climate-induced changes in soil quality, incidence of plant diseases, weed and insect populations, and enhanced food spoilage from heat and humidity. Finally, the extent to which adaptive responses are available to farmers must be considered.

Developing countries already struggle with large and growing populations and malnutrition, and would be particularly vulnerable to changes in food production. A recent analysis indicates that an additional 40-300 million people (relative to a projected baseline of 640 million people by year 2060) could be at risk from malnutrition due to climate change. [35]

Extreme Weather Events: Tropical cyclones represent the most destructive form of recurring natural disaster. Historical analysis shows that hurricanes only form in regions where sea surface temperatures are above 26˚C. [36] A recent modeling study of the western Pacific concluded that a sea surface warming of just over 2˚C would intensify hurricane wind speed by 3-7 meters per second (or 5-12%). [37] Yet hurricane frequency has not increased in the last 50 years, and current climate models lack the spatial resolution to predict a change in cyclone formation.

While hurricane predictions are still elusive, heavy rainfall events are anticipated with climate change. In the U.S., flash floods are currently the leading cause of weather-related mortality. [38] In addition to immediate drowning deaths, flood waters can cause the release of dangerous chemicals from storage and waste disposal sites and precipitate outbreaks of vector- and water-borne diseases. For example, extreme flooding and hurricanes have been responsible for outbreaks of the spirochetal zoonosis, Leptospirosis, in Nicaragua and Barbados. [39] Mosquito-borne Rift Valley fever occurs in association with El Niño-driven flooding in east Africa, [40] as demonstrated by the serious outbreak in Kenya during this year's strong El Niño.

Environmental Refugees: Sea level rise, in combination with extremes of the hydrologic cycle, could pose serious repercussions for coastal communities and cause large population displacement. 13 of the world's 20 current "megacities" are at sea level. A one-meter sea level rise would inundate low-lying areas affecting: 18.6 million, 13.0 million, 3.5 million, and 3.3 million people in China, Bangladesh, Egypt, and Indonesia, respectively. [41]

Rising seas result in salination of coastal freshwater aquifers and would threaten drinking water resources and coastal farmland. Far larger numbers than those threatened by frank inundation may be indirectly impacted in this way. For example, a one meter sea level rise could affect 60% of the population of Bangladesh and 100% of many island nations. [41] In places such as Alexandria, Egypt, agricultural depletion of groundwater and reduced siltation from upstream dams and levees are already causing land subsidence, thus decreasing the threshold for impact. Lagos, Nigeria, acquires 60% of its water from a shallow aquifer that is merely 1 meter above current sea level. Finally, sea-level rise could disrupt stormwater drainage and sewage disposal, compromising sanitation.

The multisectoral impacts of sea level rise, combined with more severe drought and floods in varying regions, may displace substantial numbers of persons.[42] "Environmental refugees" could potentially present the most serious health consequences of climate change, considering the associated risks that stem from overcrowding, virtually absent sanitation, scarcity of shelter and natural resources, and heightened tensions leading potentially to war. Environmentally forced population migration may unfold to be the largest challenge beneath the "tip of the iceberg" of climate change health impacts.

Ozone Depletion and Ultraviolet Radiation: By trapping heat at the earth's surface, greenhouse gases cool the stratosphere, which enhances chlorofluorocarbon (CFC) destruction of the ozone layer. [2] The direct health impacts from increases in UV-B include: 1) skin cancer; 2) cataract and other ocular diseases;

and 3) immunosuppression. Indirect effects to health may occur primarily through UV-mediated crop damage and by photochemical formation of tropospheric ozone.

It is estimated that for a sustained 10% decline in the stratospheric ozone layer, non-melanoma skin cancer cases could rise by 26%, or 300,000 globally per year; melanoma could increase by 20%, or 4,500 more cases annually [43]. Cataracts account for half of all blindness in the world. A 10% sustained loss of stratospheric ozone would result in nearly 1.75 million extra cataracts annually [43].

RESEARCH TOOLS AND STRATEGIES

The following research methods are among those required to address this cross-cutting, ecologically complex and long-term public health challenge:

1) Time-series and regression analysis of historical data, including analogue situations of extreme climate variability (e.g., El Niño);
2) Geographic analysis of disease incidence based on weather and landuse/landcover variables (taking advantage of Geographic Information Systems or GIS, and satellite remote sensing);
3) Scenario-based mathematical and predictive modeling with uncertainty analysis;
4) Generalized integrated assessments that include demographic, social and economic disruptions.

For any of these analytical methods, human health data is the most unreliable, due to reporting bias and variability in detection methods. There is a critical need for *capacity building* to improve surveillance and monitoring to detect changes that may be a result of global climate and ecological change. Yet surveillance alone is not sufficient to prevent illness, and continued efforts to develop predictive models should be a priority.

Comment on Modeling: Predictive models are essential to improving proactive preventive health measures. Even though no model can completely simulate real life, models are useful in conceptualizing dynamic processes and their outcomes. Although empirical studies have limits, they are the foundation upon which modeling parameters are determined. While not necessarily more accurate, mathematical models can achieve a better conceptual representation of interrelated systems. Multiple iterations of well-conceptualized models help identify key knowledge gaps; and this, rather than obtaining a "correct" model projection, might be their most valuable outcome for scientists.

Conclusion

New understanding of linkages between public health and "global life-support systems" is emerging in the literature.[44] The long-term and complex problems posed by climate change may not be readily discernible over short time spans, and may therefore demand an expanded effort in scenario-based risk assessment to be undertaken in parallel with historical validation.

The results of the studies reviewed in this article must be viewed in the context of many other environmental and behavioral determinants. Future studies must consider, along with climatological factors, key variables such as poverty, sanitation, landuse changes, and public health surveillance and mitigation programs. Studies of potential risk at the level of global climate models, while instructive, can only translate directly into actual risk or vulnerability when these local factors are included in assessments.

Analyzing the role of climate in determining human health outcomes will require interdisciplinary cooperation among health scientists, climatologists, biologists, ecologists and social scientists. Increased disease surveillance, integrated modeling, and use of geographically-based data systems will afford more anticipatory measures by the medical community. Understanding the linkages between climatological and ecological change as determinants of disease will ultimately help in constructing predictive models to guide proactive prevention.

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Climate Change, Weather Extremes And (Re)insurers

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Abstract

(Re)insurers are mainly concerned with three specific types of climate extremes: 1) major hurricanes making landfall, 2) European wind storms and floods, and 3) extremes in temperature, precipitation, and snowfall. In the cases of landfalling hurricanes and European storms, their interests are driven by their exposure to the risk of losing money. In the case of extremes in temperature, precipitation and snowfall, their interests are based on the business opportunities that are arising in the weather derivative market. The Risk Prediction Initiative (RPI) is a business-science partnership based at the Bermuda Biological Station for Research that provides a forum where climate scientists and representatives of the (re)insurance industry can interact, and it supports external research on topics of interest to the RPI sponsors. There are currently 10 companies from the reinsurance and insurance industry that sponsor the RPI. This paper provides a summary of how and why the sponsors of the RPI are interested in specific climate extremes.

Introduction

Changes in mean climate conditions and shifts in the frequency of extreme events could have serious implications for many sectors of society. Quantifying and predicting these variations is a daunting task that is being vigorously pursued by many scientists, federal agencies, and private companies. The meeting "The US-Canada Symposium on Climate Change and Weather

Extremes” held in Atlanta during October, 1999 brought together representatives from academia, the federal government, non-governmental organizations, and the private sector. The purpose of the meeting was to discuss better ways to predict, mitigate, and adapt to regional and continental scale changes in climate and weather extremes.

The (re)insurance industry is one component of the private sector that could be significantly affected by changes in climate and weather extremes. Variations in the frequency of deep freezes, longer or more severe droughts, and more frequent and/or intense landfalling hurricanes are just of few examples of future climate and weather changes that might affect insurance companies. Thus there are economic incentives to transmit information in a useable and understandable manner from the climate science community to the (re)insurance industry. This information could allow insurers and insurance regulators to set fair and reasonable insurance rates and permit (re)insurance companies to make rational business decisions.

The Risk Prediction Initiative (RPI) is a unique science-business partnership designed to satisfy the need for an efficient flow of information between the science and business communities. The main purpose of the RPI is to initiate and enhance interaction between the climate science and (re)insurance industry. The RPI and its sponsoring companies are very interested in climate change and weather extremes, particularly with regard to their relationship to a variety of climate indices such as the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO), etc. Anthropogenic climate change is not a major focus of the RPI because the range of natural variability in climate encompasses the magnitude of anthropogenic change expected to occur on the relatively short time scales that are relevant for most business decisions.

To explain why RPI sponsors are interested in specific types of climate change and weather extremes I provide background on the RPI and its sponsors from the (re)insurance industry, a brief description of reinsurance, and outline how (re)insurer’s interests have evolved over the last decade. I subsequently describe the types of climate change and weather extremes that are of interest to the companies that sponsor the RPI. This information provides insight into the needs of the (re)insurance industry.

Overview of the Risk Prediction Initiative

The RPI was founded in 1994 and is based in Bermuda at the Bermuda Biological Station for Research, Inc (BBSR). The major event that catalyzed the formation of the RPI was the magnitude of insured losses from Hurricane Andrew hitting Florida in 1992. The size of the insured loss (around $18 billion in 1998 dollars) was greatly in excess of the largest loss that was predicted by the risk models in use at that time. The losses caused the bankruptcy of a number of insurers and led to a severe capital shortage in the reinsurance industry. In response to this business opportunity, a number of catastrophe reinsurers were formed in Bermuda to supply the need for capital. Bermuda was an ideal setting for the catastrophe reinsurers because of its advantageous tax laws, the stable and responsive government, and its proximity to the United States. Scientists at BBSR formed the RPI with the support of a variety of catastrophe reinsurers based in Bermuda, reinsurers from the United States, and other US companies active in the insurance industry. The current RPI sponsors are listed in Table 1.

Table 1. Current Risk Prediction Initiative Sponsors

Ace USA, Inc.	X. L. MidOcean Reinsurance Company, Ltd.
Renaissance Reinsurance Corporation	Zurich Group/Centre Solutions Ltd.
General Reinsurance Corporation	Employers Reinsurance Company Ltd.
AIG/IPC Reinsurance Company Ltd.	USAA
State Farm Insurance	American Reinsurance

The overall goal of the RPI is:

> *To create links between the climate science and insurance communities so that the science of climate forecasting is available, understandable, and usable by insurers.*

Three activities are used to achieve this goal: 1) RPI-funded external research, 2) the development of in-house products, and 3) RPI-hosted workshops. I next describe the products and results of each of these activities to illustrate the type of information that interests the companies that sponsor the RPI.

The RPI funds three types of external research: 1) the extension of historical records of major hurricane landfalls along the Gulf and East Coast of the United States using geological records, 2) the development of seasonal and multi-annual hurricane landfall forecasts and the analysis of how climate variability affects tropical cyclone activity, and 3) the analysis and modeling of tropical cyclone wind fields. Leading scientists at universities and federal laboratories throughout the world undertake research on each of these topics. The research results are not proprietary, in fact, the RPI encourages peer-reviewed publication of research in order to insure quality results.

In-house products developed by the RPI are mainly aimed at making existing knowledge more useable and available for RPI sponsors. Examples of in-house products include the development of a tropical cyclone prediction model based on techniques published by Dr. Gray and his colleagues and the analysis and synthesis of other existing data.

RPI-hosted workshops (Table 2) are used to achieve a variety of goals. Some workshops are used to develop a research agenda that identifies questions of particular relevance to the insurance industry, some are used to assess the state-of-the-art in a given field, and some are used to explore areas that will potentially receive research dollars from one of the RPI Research Groups.

Table 2. Recent workshops hosted by the Risk Prediction Initiative

Workshop	Year
Uncertainty of damageability	1999
Hedging with weather derivatives: How reliable are seasonal predictions of temperature and precipitation	1999
European wind storms and the North Atlantic Oscillation	1999
The transition of tropical cylcones to high-latitude storms	1998
Wind field dynamics of landfalling tropical cyclones	1997

Primer on Catastrophe Excess of Loss Reinsurance

Reinsurance is designed to handle extreme events that affect an *insured* segment of society. Insured is italicized in the previous sentence to emphasize that if an extreme event affects a segment of society that is not covered by the reinsurance industry, for example a super-typhoon hitting Bangladesh, or widespread flooding in the United States, then the event has little impact on the reinsurance industry[4].

The top five insured losses between 1970 and 1998 are listed in Table 3. Note that weather events are responsible for 4 of the top 5 insured losses. Despite the large insured losses, there are relatively few deaths. Many severe events that kill thousands of people, for example Hurricane Mitch, do not make this table because they occurred in regions with little or no insurance. Hurricane Andrew caused the biggest loss due to natural disasters. This is consistent with the fact that the major extreme weather event that interests the (re)insurance industry is the landfall of an intense, or major, hurricane along the Gulf and East coasts of the United States.

Table 3. Top five insured losses, 1970-1998.

Event	Date	Deaths	Insured Loss (Billions 1998 $US)
Hurricane Andrew	1992	38	18
Northridge Earthquake	1994	60	14
Typhoon Mireille	1991	51	6.7
Winter Storm Daria	1990	95	5.7
Hurricane Hugo	1989	61	5.5

Source: Swiss Re Sigma no. 1/1999

Reinsurance is basically insurance for insurance companies. An individual buys insurance for protection against a high-consequence, low-probability event. An insurer achieves analagous protection from high-consequence, low-probability

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[4] The reason for the small impact on the reinsurance industry differs for these two examples. Insurance is not widely used in Bangladesh, and as a result, there is little or no market for reinsurance. Insurance is commonly used in the United States; however, the federal government provides residential flood insurance. In practice the federal government self-insures and does not use reinsurance.

events by buying reinsurance. Reinsurance also lets an insurer increase its business by allowing it to sell more insurance.

Consider a two-dimensional space defined by event intensity and event frequency (Figure 1). A primary insurer is able to use its own capital to handle the high probability, low intensity events (e.g., a very small earthquake or a thunderstorm). However, it is too expensive for an insurer to keep large amounts of capital that will be required if a relatively low probability, high intensity event (e.g., a large earthquake or landfall of an intense hurricane in a densely populated area) occurs. An insurer will buy reinsurance to guarantee access to capital after an intense event so that the company can pay policyholders.

Catastrophe excess of loss (CatXL) reinsurance is probably the most common type of catastrophe reinsurance. CatXL reinsurance is generally structured in layers. The cost for reinsuring a given layer tends to decrease as the probability of the event decreases (e.g., moving from reinsurance layer 1 to 4 in Figure 1). A given reinsurance layer can be covered by one company, or shared by multiple companies. In addition, the insurance company is usually required by reinsurers to retain some risk, or liability, for each layer as a way to control inflated losses or claims. There is generally an upper limit to the amount of reinsurance a company can afford so that losses beyond a given level are ultimately the responsibility of the primary insurer.

Catastrophe reinsurance rates fluctuate with time and are affected by a variety of factors. Reinsurance rates generally go up dramatically after a major insured loss and then start to decrease as the time since a major loss increases. In addition, natural disasters that occur in the United States tend to have the biggest effect on reinsurance rates because the United States is by far the largest source of reinsurance premiums in the world. There have been no natural disasters that have caused major losses to reinsurers since Hurricane Andrew, as a result, reinsurance prices have fallen dramatically from their high levels in the early 1990s. This situation is at odds with the

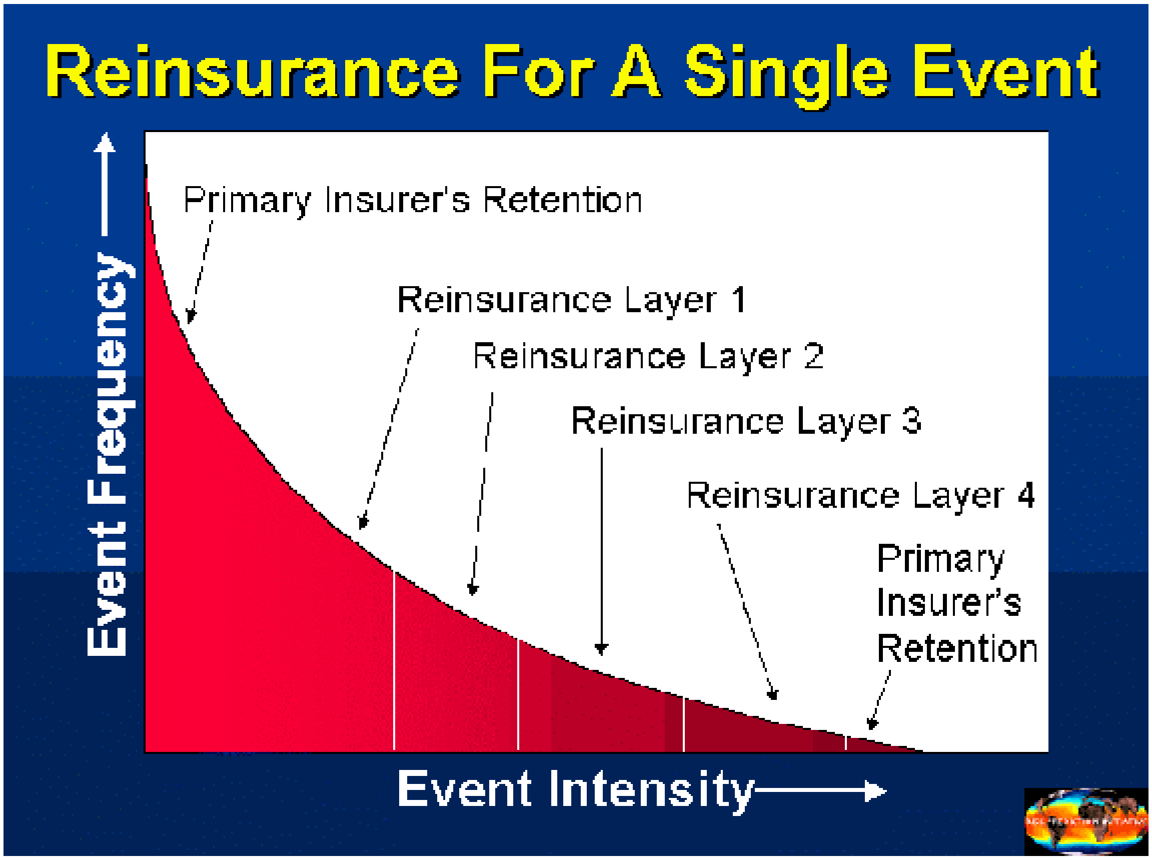

Figure 1. Schematic diagram showing how insurance and reinsurance is distributed over a plane defined by event

fact that the long term probabilities of an extreme event, although poorly known, are relatively constant[5].

The drop in reinsurance prices coupled with the need for a company to maintain an adequate return has had two effects in the reinsurance industry. The first is that there has been a dramatic consolidation in the reinsurance industry. The second is that the reinsurers are looking for new markets for their skills. One of the more interesting markets for reinsurers is the development of the weather derivative market, mainly the degree day products. The allure of this new product is the reason many reinsurers are now interested in seasonal forecasts of temperature and precipitation and in knowing more about extremes in temperature and precipitation.

Climate Extremes of Interest to RPI Sponsors

The three major extremes of interest to RPI sponsors are: 1) landfall of an intense hurricane along the Gulf and East coast of the United States, 2) European wind storms and floods, and 3) extremes in temperature, precipitation, and snowfall on a variety of time scales. The motivation for the insurance industry's interest in the first and third items is clear from the preceding discussion. European wind storms and floods are of interest because they cause the largest insured losses in the second largest insurance market in the world[6].

What type of information on climate extremes is most important for the (re)insurance industry? Forecasts of future events and event probabilities based on the historical record are possibly the two most useful types of climate extreme information for the (re)insurance industry. Which of these two is most important depends on the context in which the information will be used. Event probabilities based on the historical record are typical of the information actuaries have traditionally used to help underwriters make decisions on whether to accept a given risk. This type of information is commonly used to set insurance prices and to guide the development of risk models.

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[5] The probabilities of an extreme event are not constant. For example, during an El Niño there is a lower probability of a hurricane making landfall in the United States than during a La Niña. However, these shifts in probability are smaller than changes in the price of reinsurance.

[6] In contrast to the United States, flood insurance in European countries is generally provided by private companies.

The (re)insurance industry is still learning how to best use climate and seasonal hurricane forecasts. The companies cannot use this information to change prices in response to changes in forecasts for a least two reasons. Firstly, a company will lose clients if it "arbitrarily" changes its pricing from year-to-year. Secondly, many insurance markets are regulated and rapid changes in prices are not possible. However, (re)insurers can use the shifts in probability to their advantage. For example, a company can alter its retrocession practices to increase or decrease their exposure to loss. Also, the development of "Catastrophe" bonds allows a company to trade risk in the financial markets. Finally, there are private exchanges (e.g., CATEX) that allow companies to electronically trade risk.

The following sections discuss specific aspects of the three major climate extremes of interest to (re)insurers.

Landfalling Hurricanes

Major hurricanes making landfall in populated regions of the United States have produced some of the largest insured losses in the world (Table 2). The magnitude of these losses is the primary reason why landfalling hurricanes are the climate extreme of most interest to (re)insurers. The insurance industry's interest in the subject can be broken into three parts: 1) a better understanding of the long-term probability of a major hurricane making landfall along the Gulf and East coasts of the United States, 2) improving the skill of seasonal and interannual forecasts of the probability of a major hurricane making landfall in the United States, and 3) augmenting our knowledge of the relationship between and a variety of climate indices (e.g., ENSO, PDO, and the NAO) and tropical cyclone occurrence and dynamics.

A better understanding of the probability of a major hurricane reaching landfall is needed to realistically determine the cost of (re)insurance. The actuarial practices used by the insurance industry assume that past occurrences of an event can be used to accurately estimate the future probability of a similar event. However, this approach is limited when dealing with the probabilities of rare, extreme events such as the landfall of a major hurricane. For example, there have been only two Category 5 (the most intense hurricane classification) hurricanes to make landfall in the United States over the last century. This record is not sufficient for confidently determining landfall probabilities along the whole coast of the United States.

The RPI funds a research program that uses geological records of intense hurricane landfall to extend the record of intense landfalling hurricanes. Sand layers in coastal lakes and marshes produced by overwash events associated with storm surge from a hurricane are an example of the geologic record left by a landfalling hurricane. Scientists supported by the RPI are collecting and analyzing cores from lakes and marshes along the Gulf and East coasts of the United States to determine the frequency of intense hurricane landfall over the last thousand years. The great value of landfall probabilities based on geological records is that they are the only way to verify model-based estimates of landfall probability.

The RPI also supports a variety of efforts aimed at improving our ability to improve seasonal and interannual forecasts of hurricane occurrence. The RPI has increased the awareness of scientists that a hurricane forecast is more valuable if it focuses on hurricanes that make landfall instead of predicting total hurricane activity in a basin. The RPI has also raised awareness that a hurricane forecast will be more valuable to the reinsurance industry if it is made in December rather than April or June. A December forecast is more valuable to the reinsurance industry because most reinsurance contracts for the upcoming hurricane season are written in December. It is more cost effective for a (re)insurer to make decision on whether to buy or sell coverage in December than it is to try to adjust their risk exposure just before the hurricane season.

Over the last several years a general awareness has arisen that the probability of hurricane landfall varies with the state of global climate. As our ability to predict climate changes on seasonal time scales improves, some (re)insurers are starting to incorporate this information into business decisions. However, (re)insurance prices are insensitive to the fact that landfall probability varies with time and it is rare that a (re)insurer will base a business decision solely on the state of climate or a hurricane forecast. The industry’s awareness that climate state affects landfall probability motivated the RPI to develop a model that can be used to predict how landfall probability varies spatially as a function of climate, and to fund several research projects that examine the relationship between tropical cyclone activity and ENSO.

European Wind Storms and Floods

The European catastrophe reinsurance market is the second largest in the world. The wind storms and floods that cause the large losses to catastrophe insurers have not been a major focus for the RPI sponsors primarily because of decision to direct limited resources towards tropical cyclone research. Risk modeling companies have responded to the interest in European storms and floods through the development of models that can estimate losses and loss probabilities.

The long historical record available at many locations in Europe is an advantage when trying to estimate the probability of a low frequency, high intensity event. For example, there are documented changes in the frequency of intense storms and the location of storm tracks over the last 150 years. One of the main factors correlated with intense storm frequency and location in Europe is the NAO. Unfortunately, the sign and magnitude of the NAO is not very predictable. In addition, it is time consuming to reconstruct the historical record of storms, thus very long historical records are available for only a few locations.

(Re)insurers would be interested in knowing more about the probability of intense wind storms and floods in Europe and how the probability varies as a function of the NAO and other climate indices. In addition, seasonal forecasts of wind storm and flood probabilities would be useful. As with seasonal forecasts for landfalling hurricanes, the value of these forecasts will vary as a function of the time of year when they are issued. This is because many of the business practices related to catastrophe reinsurance in Europe are the same as in the United States.

Seasonal Extremes in Temperature, Precipitation, and Snowfall

The analysis of historical records and seasonal forecasts are the major items of interest to (re)insurers involved in the developing market for weather derivatives. Most of the current market is based on degree day contracts, however, there are some contracts based on precipitation and snowfall. The number of heating degrees in a day is the difference between 65˚F and the average of the minimum and maximum temperature in a 24 hour period if the average is less than 65˚F. The number of cooling degree days is the difference between the average of the minimum and maximum temperature in a 24 hour period and 65˚F if the average is greater than 65˚F.

The RPI recently held a workshop to identify specific items of interest to the RPI sponsors that are members of the Weather and Climate Research Group. The following items were identified as particularly interesting and were the topic of a Request For Proposals that was issued by the Risk Prediction Initiative:

B. How to define the period for a climatological normal
C. How to handle temperature records at urban stations
D. What is the spatial correlation in anomalies between different stations, and
E. What is the correlation between temperature anomalies and different climate indices

The definition of a climate normal is of great importance because the contracts are based on expected means and variances that will vary as the time period used to define the climate normal changes. This question is also of great importance given the relatively warm global climate in the 1990s. There is uncertainty in quantifying how much of the warming is anthropogenically induced, and will therefore likely continue, and how much the warming is related to a climate cycle, and therefore likely to wane at some point in the future.

The reinsurers' interest in urban stations differs from that of most climate researchers. Typically, a climate researcher avoids stations near urban areas because of "heat island" effects and other problems associated with urbanization. However, urban stations are where the benefits of weather contracts are the greatest and data from these stations are used in weather contracts.

The interest in spatial correlation arises from the reinsurers' practice of diversification. There is a relatively low chance of correctly predicting the number of degree days at a given station. However, there is a much better chance of predicting the number of degree days associated with a portfolio of stations. One must know the correlation between stations to properly diversify a portfolio.

Seasonal forecasts of temperature and precipitation are used to some extent to negotiate weather contracts, but most (re)insurers base their business decisions more on the historical record. An estimate of the correlation between a climate index and temperature anomalies at a station will make seasonal forecasts more useful to reinsurers participating in the degree day market.

Summary

(Re)insurers are mostly concerned with three major climate extremes: 1) major hurricanes making landfall, 2) European wind storms and floods, and 3) extremes in temperature, precipitation, and snowfall. In the cases of landfalling hurricanes and European storms, their interests are based on their exposure to risk. In the case of extremes in temperature, precipitation and snowfall, their interests are based on the business opportunities that are arising in the weather derivative market.

The RPI provides a forum where climate scientists and representatives of the (re)insurance industry can interact and it supports external research on topics of interest to the RPI sponsors. There are three research groups currently active in the RPI. The research groups focus on bettering our knowledge of the record of major hurricane landfall, improving seasonal forecasts of hurricane landfall, and on developing an ability to predict and understand temperature, precipitation, and snowfall anomalies.

At this time the RPI has little emphasis on understanding and predicting how extremes might change in the future due to anthropogenic influences. On business time scales the range of natural variability is thought to be larger than any change due to anthropogenic forcing and accounts for the current lack of emphasis on anthropogenic change.

The (re)insurance industry is highly skilled at using statistical data. Therefore forecasts or analyses of the probability of past extreme events are most valuable if they include complete probability distributions instead of simply providing estimates of the mean value.

Society’s Vulnerability to Weather Extremes

Oct., 1999

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Introduction:

The purpose of this paper is to address society’s vulnerability to weather extremes. The sections that I have been instructed to address include the range of potential physical effects, what makes an extreme event a disaster, the ways in which human systems are vulnerable, the relative roles of climate and non-climate factors in creating social vulnerability and the role of climate change with respect to trends in disaster occurrence. This is a challenging task, to say the least, and justice cannot be given to it in one talk, one paper, or probably by one author. I hope, though, that I have at least presented some ideas that will generate further discussion.

(1) Range of Potential Physical Effects

The range of physical effects on our social system from extreme events range from nil to devastating. In the trivial case where the events occur over a natural setting, or where the resistance and/or resilience of the built environment exceeds the scale of the weather event, impacts are not significant. Other events are far from trivial, such as the F5 tornadoes in Oklahoma last summer, or Hurricanes Andrew or Mitch.

Natural hazards and the disasters associated with them have widely disparate origins and characteristics. They can be classified by their magnitude, intensity, frequency, duration, extent, speed of onset, and predictability (Burton et al., 1993), and each is unique. Some events, such as earthquakes, occur without clear warning. Flash floods, and tornadoes often, but not always, come with some warning, though it might be only minutes. Hurricanes have long warning lead times. Some disasters are extremely localized, like tornadoes or landslides; in contrast, hurricanes sweep across large regions. Drought is an example of a disaster that builds slowly and tends to be widespread, its impact accumulating over several months or years.

(2) What makes an extreme event a disaster?

Natural disasters occur when a natural event such as a storm 'occupies' our space, and triggers social vulnerability, with a resultant damage to the physical and social fabric that exceeds the ability of the affected community to recover to the pre-disaster state without assistance. Occasionally 'great' or 'mega' disasters occur, where the need for recovery becomes truly national and/or international. An recent example of this was the horrendous damage inflicted on Honduras by Hurricane Mitch in November, 1998, which destroyed large amounts of infrastructure and cost 11,000 lives.

In meteorology and geophysics, the definition of an extreme event is arbitrary. Increasing event magnitude and decreasing frequency are modeled by smooth probability distributions without discontinuities. From a damage perspective though, the definition of an extreme event is defined by the design criteria of our built environment, which creates thresholds in the 'damage probability function' that do not exist in the natural trigger. Disasters tend to lie to the right of these thresholds on the usual graphs.

It is important to distinguish between the cause of a disaster, and its trigger. While a severe storm may be a trigger, the causes of a disaster are far more complex, including all the social processes that create vulnerability. This common confusion between 'trigger' and 'cause' affects peoples perception of natural disasters, in the sense that responsibility for them tends to be assigned to the trigger (nature), thereby minimizing the role society plays in their formation.

(3) In what ways are human systems vulnerable?

There is a simple answer to this question. If it rains too much, or if the wind blows too hard then human systems are vulnerable. But the issue of what is too much, and how those thresholds have been created invokes a host of complicated and subtle issues involving psychology, risk perception, politics, and culture to name a few. A conceptual model called the Disaster Adaptation Cycle (adopted from Blaike et. al., 1994) illustrates how disasters occur . This model shows the cyclic interaction between the hazardous environment and society's adaptive decisions. With respect to risk, a disaster is shown to occur when a hazardous event triggers an existing vulnerability. The occurrence of a disaster tends to create a burst of overlapping human activities, beginning with response and recovery, but also including longer-term endeavours such as mitigation and preparedness. These activities feed back into the risk evaluations, and can reduce our vulnerability if they are done well, or increase it if done poorly. Subsequent disasters are affected by outcomes resulting from previous ones, in an ongoing cycle of adaptation.

Perceptions have an impact on the severity of a disaster. Since extreme events occur more rarely than minor ones, people tend to develop a false sense of security. Unfortunately, society often does not incorporate high-risk, low-probability events into cost-benefit analyses. When people perceive that their risks have been reduced as a result of technology, they will tend to act in more risky ways if voluntary actions are available to them (Wilde, 1994).

Designing appropriate mitigation responses can be made difficult by false beliefs; the 1942 movie 'Bambi' and the creation of the symbolic cautionary figure 'Smokey the Bear', contributed greatly to the since-discredited notion that fire is always bad for forests (Nash, 1985). It has been said that Bambi did more to define the philosophy behind fire suppression in North America during the last 50 years than all the scientific research combined. Modern news media also generate myths, exaggerating the risk of some hazards and downplaying others. Generally, the public is willing to accept voluntary risks (e.g., driving a car) at about 1,000 times the magnitude of involuntary ones (e.g., getting hit by lightning) (Raphael, 1986). Understanding how communities perceive risks and the origin of risks is necessary before methods of encouraging appropriate response can be found.

Historical disasters provide insight into society's vulnerability. They can also, at times, induce complacency if it is commonly believed that they represent the worst that could happen, though in fact they are rarely a worst-case scenario. A single, high-magnitude earthquake in Vancouver or lower Quebec, hitting Ottawa and/or Montreal, could cost CAN$14 billion to CAN$32 billion (Canadian National Report - IDNDR, 1994). A storm similar to Hurricane Andrew striking Miami would have expected losses of US$48 billion to US$80 billion (Changnon et al., 1997). A recurrence of the December 16, 1811, New Madrid, Missouri, earthquake of magnitude of 8.6 could cause damages of US$138 billion (Friedman, 1992). A major eruption, without warning, of the Popocatépetl volcano near Mexico City could cause one of the worst volcano disasters in history.

Risk transference occurs as a result of poorly thought-out or applied mitigation, which tends to (1) create or magnify thresholds since it only protects society up to specified levels of risk, and (2) increase long-term vulnerability. For example, development may not be allowed within the 100 year flood plain, while there is no restriction (and likely no required flood-proofing measures) outside of it. Buildings are built to withstand specified loads of snow, wind or groundshaking (typically at 30 to 50 year return periods, though higher values are more common for earthquake resistant structures), but will fail when loads exceed those designed for. Risk is then reduced for natural triggers up to the specified value. If society were otherwise unchanged by a particular act of mitigation, then true risk reduction would be achieved. Unfortunately, however, all too often mitigation increases long-term vulnerability: especially when risk is transferred from the more frequent low-impact events to the rarer high-impact events, resulting in increased long-term vulnerability.

This occurs, in part, because of people's perceptions. The principle of '*risk homeostasis*' (Wilde, 1997) suggests that people tend to operate at what they perceive to be an '*acceptable level of risk*'. When they perceive that their level of risk has decreased, they will tend to act in increasingly riskier ways until they have again reached their acceptable level of risk, given that voluntary actions are available to them. Thus, if people perceive that they are protected by technology (e.g. levees or dykes), they will tend to increasingly develop in the protected areas (e.g. Tobin and Montz, 1997) unless prevented by land-use planning or economic disincentives.

This would not necessarily increase long-term vulnerability if human behaviors were consistently based on a realistic estimate of long-term risks. But, though people are pretty good at incorporating the risk of more commonplace hazards into their subjective risk analyses, they are not very good at doing so for rare high-consequence events that tend to be discounted (events that have not been previously experienced tend not to be perceived as worth taking account of (Slovic, 1986)). Scientific analyses can underestimate risks as well, since the probability of rare events can be very hard to determine from relatively short observational records. Some recent paleoclimate analyses that suggest that the world has been in a relatively benign climate for the past century or more, but may be moving towards a more hazardous state, makes statistical estimations even more uncertain.

Even should the probability of hazardous events be accurately known, short-term thinking can result in their being ignored, as in the case of development along well-known fault lines in Tokyo, Japan, British Columbia, Canada and California, U.S. Losses resulting from these sorts of hazards have been noted by Munich Re. (1997), who found that "*the extent of loss has not infrequently been increased through a false assessment of the risk circumstances or in the pursuit of profit*". Thus the amount of development arising from the perception of reduced risk tends to be disproportionate to the real increased risk from rare events - and long term vulnerability is increased.

An important issue with respect to vulnerability relates to the difference between an infrastructure that is resistant, and one that is resilient. To explain by example, a house resistant to floods has a dyke around it, while a house resilient to floods is a house that floats. The recent Canadian Ice Storm disaster of 1998, illustrates the vulnerability of a system designed to be resistant, but not resilient.

(4) Relative role of climate and non-climate factors in creating vulnerability..

The answer to the question 'How important are climate vs. non-climate factors in creating vulnerability?' depends upon your world-view. In the hazard/disaster community, there are two opposing perspectives. The first views disasters as 'Acts of Nature or God'. The second views them as 'social constructs'. The philosophical bases for these two approaches are quite different. The second approach is based on a paradigm that humankind cannot and probably should not try to control nature (at least not all of the time) and it is preferable to arrange society around hazardous regions.

It seems to me that the followers of the first paradigm are split into 2 groups, one which is fatalistic and another which believes that humankind can prevent disasters through technology (i.e. that man can and should control nature and that it is preferable to arrange hazardousness around society) - but that when technology fails and disasters occur, then 'nature' is to blame. Both these world-views inevitably lead to a worsening disaster experience. Unfortunately, it is the 'Acts of Nature or God' approach that has been the traditional one (Haque, 1997, 1998; Hewitt, 1997), though it is coming under increasing criticism, and mitigation programs such as run by FEMA in the USA and EPC in Canada are now placing more value on moving out of harm's way.

There is a danger in labelling a disaster as 'natural', as opposed to technological, social or political. The danger lies in the perception that disasters of natural origin are beyond society's control; like 'Acts of God', they are 'Acts of Nature'. This is the essence of acceptance and fatalism, a philosophy that results in a continued, or possibly worsening disaster experience. The antitheses of this world-view, rooted in an understanding of the dynamic, complex and closely linked interaction between nature and humankind, provides a basis for mitigating the impacts of disasters by creating a society resilient to extreme events.

(5) Role of climate change with respect to trends.

Global change, both in the natural and human spheres, seems likely to exacerbate disasters in the future. The anticipated changes include more frequent and severe extreme weather events due to climate change, changes in wealth and land-use, and increases in and migration of populations.

One important facet of global change relates to the climate. Greenhouse gases in the atmosphere, which warm the surface of the earth, are one of the most important parts of the climate system. Industrial emissions and deforestation are rapidly increasing the concentration of these gases in the atmosphere. Today’s atmospheric concentration of carbon dioxide far exceeds any value in the past 200,000 years and is expected to double before the end of the next century. The concentrations of other greenhouse gases such as methane are also increasing rapidly. Climate models predict that these changes will soon alter the earth’s climate. More frequent and extreme events, such as heat waves, severe thunderstorms, floods, and droughts, and a rising sea level, seem likely to be a part of this new climate. Even relatively small changes in averages can result in more frequent extreme events (White and Etkin, 1998).

It is not clear what the precise relative role of climate change is, in terms of defining our disaster experience. Primarily, I view natural disasters as primarily a social issue. This may change in the future, however, if our social ‘climate assumption’ of relative stability is proven wrong. How climate change will affect us, locally, is very uncertain, and this uncertainty has important implications for our decision-making, in the sense that we need to emphasize resilience as well as resistance. To explain by metaphor, pro-active adaptation to climate change requires designing a society with fewer dykes, and more floating houses. By creating a society with more local resilience to disasters now, we buffer ourselves against the risks associated with future disasters exacerbated by a changing climate.

(6) Concluding Remark

Vulnerability to natural hazards varies greatly from country to country, and region to region. Society is vulnerable when poverty or a lack of access to resources restricts people's ability to live in safe locations or safe buildings, or to buy insurance, when the risks of rare extreme events are not incorporated into cost-benefit analyses, when adaptive behaviours are based on poor assumptions, or when people do not pay sufficient attention to the laws of nature and choose to live in harm's way. Ultimately, society is vulnerable when an extreme event exceeds the design criteria of its adaptations. Though nature provides the hazardous environment, society designs its own disasters through its adaptive decisions.

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DEALING WITH WEATHER EXTREMES:
CURRENT STRATEGIES AND FUTURE DIRECTIONS

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I. INTRODUCTION

Good afternoon. My name is Mary Fran Myers. I am the Co-Director of the Natural Hazards Research and Applications Information Center at the University of Colorado, in Boulder. I am delighted to have this opportunity to share this session to introduce you to society's vulnerabilities to weather extremes with my colleague, Dave Etkin.

Dave has done an excellent job of providing you background on the impacts of extreme events, on disasters, and on vulnerability. Now to add to that mix of information, I will use my time to talk about the trends in strategies that societies in Canada and the U.S. have used to deal with extreme events, where those trends have led us, and then share with you some ideas about where our hazard mitigation programs should be headed in the future if we are ever to curb the rising losses due to natural hazards, based on the results of a five year study our center released this year.

II. CURRENT STRATEGIES

Losses from extreme weather events, as Dave pointed out, are a function of the relationship between extreme meteorologic phenomena and society's built environment. Traditionally, society has dealt with extreme weather events, by trying to manage the events in order to limit losses from them. This management of hazards a piece of the Disaster Adaptation Cycle of which Dave spoke can be characterized by three different types of activities: (1) those which seek to modify the hazard, (2) those which modify the vulnerability of people and the built environment to damage from disaster, and (3) those which modify the impact of a disaster. These various strategies are frequently referred to as "mitigation tools" (or what is referred to as "adaptation" in climate change lingo) and are carried out before, during, and after disasters. In practice, they overlap, though each has its own aims and serves as a building block for the others.

Modify the Hazard

Modifying the hazard, of course, refers to human efforts to change Mother Nature not necessarily the wisest thing for us to do. Efforts to modify climatological events range from weather modification programs to structural flood control systems where humans actually try to control how much and where rain might fall or control the flow of rivers and the direction they take.

Modify Susceptibility

Modifying susceptibility to vulnerability generally refers to nonstructural approaches to dealing with hazards and there are a variety of activities that can be undertaken to do that. For ease's sake, I group them into four general types of categories.

1) Information and Education

Generally, the more the public and local officials know about the risks they face from climatological phenomena and how they might protect themselves from danger, the better equipped they are to deal with those phenomena when they are in the extreme category. Societal knowledge about risk is extensive. And, the format in which that information is distributed is also extensive. We have maps that show high hazards from floods, storm surge, landslides, and more. Agencies such as the Federal Emergency Management Agency (FEMA) and Emergency Preparedness Canada develop and distribute materials ranging from brochures to technical manuals on emergency preparedness and response. There are a number of educational programs that have been sprouting up around the country that offer training in hazards and emergency management. The Internet is a new tool we have this decade and provides more information than a person can actually absorb about hazards. In terms of the societal aspects of climate and weather extremes, in my opinion, the very best Internet source is the National Center for Atmospheric Research's page: Societal Aspects of Weather which can be found at http://www.dir.ucar.edu/esig/socasp/

2) Guiding Future Development

Another way in which vulnerability to extreme weather events can be reduced is by trying to be a little smarter about where new development occurs. A range of tools, including building codes, comprehensive land use planning, community facility planning, growth management and capital improvement planning are available to local governments so that when natural hazards do strike, damage to the built environment can be limited. For example, in areas subject to high winds (such as tornado alley) codes can require hurricane-wind strength connectors for roofs and corners to increase structural integrity. In flood prone areas, houses can be elevated. Land use plans that guide development away from hazardous areas (e.g., areas prone to flash floods, storm surge, or landslides) allow communities to make decisions to avoid future damage. Comprehensive stormwater management programs enable a community to prepare for heavy rains by providing storage areas for the excess flow of water.

3) Forecast and Warning

Lives can be saved if reliable forecasts are available, if appropriate warnings are issued, and if people and organizations take suitable actions upon receipt of those warnings. Hurricane Floyd gave us a good example of this just last month.

The people in this room probably know better than me that the scientific capability for predicting weather and weather patterns has improved greatly in the 20th century. Yet forecast and prediction are only one part of the picture. To use them effectively to reduce society's vulnerabilities, the information scientists have must be relayed in a way so that the audience that hears it (be it an individual or a local emergency manager) behaves in an appropriate fashion.

Severe weather warning systems involve complex processes.

Providing effective warnings of severe weather to people requires a chain of events, beginning with the technology to observe and predict the weather and ending with risk communication and human response. These components of warning systems are interdependent, making the system only as good as its weakest link. Good warnings will include information about the probability of a severe event, its location, and the time frame involved, and also give people information on appropriate actions to take in response to the warning.

4) Disaster Preparedness and Emergency Response

Disaster preparedness involves building an emergency management capability in advance of an event in order to facilitate an effective response. Critical to disaster preparedness is development of a vulnerability analysis that identifies the hazards of a particular place. Preparedness also includes the necessary planning for emergency response. There are six basic functions that are carried out during response activities: hazard detection and warning; evacuation of threatened populations; sheltering of and caring for victims; provision of emergency medical care, food and shelter; conduct of search and rescue operations; and provision of security and protection for property. Other specific functions (dependent on the event) also may be called for in the response phase. For example, severe thunderstorms can cause loss of power facilities, which requires the provision of emergency power supplies.

Modifying the Impact

The third strategy society uses to reduce vulnerability to extreme events is to modify the impact of an event, or in other words, to spread the loss from them. It's important to note that this strategy does not reduce the loss... it just spreads it around to all of us.

Insurance

Insurance is one tool we have to relieve the financial burden on victims of disaster and taxpayers by spreading the cost of disasters among a broad group of policy holders. Property damages caused by some extreme weather events (e.g., by hail or lightning) in the U.S. and Canada are generally covered by an individual homeowner's property and casualty policy. In many cases, wind damages are covered as well (though sometimes it is required as an extra "rider" in hurricane prone areas). In the U.S. damages due to flooding are covered only if the property owner holds a special flood insurance policy; in Canada insurance to cover flood damages to residential structures is not available, though it is available for commercial structures.

Disaster Assistance

Disaster relief programs of governments and non-governmental organizations (NGOs) also serve to lessen the impact of disasters on victims. In the U.S., the availability of public disaster relief is limited unless a presidential disaster declaration is made. If this is the case, the type of relief provided might include low-interest loans, small grants, temporary housing, and 75% of the costs of damage to public facilities. In cases of the latter, state and/or local government are required to pay the remaining 25%. For the more common, less catastrophic event, people must rely on insurance payments or funds from NGOs such as the Red Cross and other voluntary or church relief groups to recoup their losses. In Canada the federal government provides disaster assistance when costs exceeds $1 per capita. They will then pay for one-half of the next $2 per capita cost, three-quarters of the following $2 per capita and 90% of the remainder.

III. THE RESULTS AND WHY

This approach to dealing with disasters or extreme environmental events has been evolving over the past several decades. From a social policy perspective, the community of people I most interact with feel that hazard mitigation - a multi-pronged approach to dealing with hazards - has really been a recognized discipline only since the 1960s, and of course we have been "adapting" in some ways to these extreme events for a much longer time.

Where has this comprehensive approach gotten us? Based on the statistics Dave quoted earlier, we could say "not very far." It seems losses due to natural hazards, including extreme environmental events, have been continually rising. The dollar figures alone are worrisome enough to make us question conventional wisdom about the effectiveness of our loss reduction programs. In addition, though too few to generalize, a few studies have been done on specific mitigation programs to assess whether or not they are having a desired result: that result being a more resilient, less-likely-to-suffer-damage society.

For example, a study done earlier this year by Jean Rousselle and his colleagues at Ecole Polytechnique de Montreal, found that two mitigation measures designed specifically to reduce future damages from floods - a floodplain mapping program and a dyking program - have made no difference whatsoever in the amount of new development or value of properties in floodplains. A study that both Dave and I were involved in within the last year and a half looked at the effectiveness of recovery assistance provided in the wake of severe flooding in Canada and the US. We found that while in some instances, the assistance did contribute to future "resiliency" (especially in the US where hundreds of structures were permanently removed from flood prone areas), in large part, most disaster relief simply rebuilt and replaced what was lost, and will be lost again in the next flood.

These two studies tend to validate the findings of a five year study that was conducted under the direction of my Center's director, Dennis Mileti, and that was released earlier this year, called *Disasters by Design: A Reassessment of Natural Hazards in the United States* (Joseph Henry Press, 1999). The study took stock of knowledge in the U.S. about what we know and don't know about natural hazards. The sobering fact is that despite society's scientific knowledge regarding the causes of extreme events and technical capability to make accurate predictions of time and place of occurrence, damages are continuing.

The study, which involved 132 experts from all applicable disciplines, discovered that the root of the problem is that disaster losses are not the result of unexpected events; rather they are the predictable result of interactions among our physical environment that produces hazardous events, the social and demographic characteristics of the communities that experience them, and the built environment in which people live.

While losses are growing partly from the fact that the nation's capital stock is expanding, they also stem from the fact that all these systems and their interactions are becoming more complex with each passing year. The three main influences at work are the earth's physical systems which are constantly changing; the recent and projected demographic composition and distribution of the population mean greater exposure to many hazards; and third, the built environment public utilities, transportation systems, communications, and homes and office buildings are growing in age and in density, making them more vulnerable to natural forces.

A central problem with our current approach is that many of the accepted methods (all the mitigation strategies described above for coping with hazards) are based on the fantasy that people can use technology to control nature and make themselves totally safe.

This has resulted in a major problem that has become clear over the past 20 years: some efforts to head off damages from natural hazards only postpone them. For example, communities near dams or levees often put themselves at risk by encroaching on areas that the structures cannot protect if they are ruptured. This contributed to catastrophic damage from the 1993 floods in the Mississippi basin. And many of the nation's dams, bridges, and other structures are approaching the end of their designed life, revealing how little thought their backers and builders gave to events 50 years hence. Similarly, by providing advance warning of severe storms and thus alleviating some of the risk of living near the ocean, the nation may well have encouraged more people to build in fragile coastal areas. Such development, in turn, makes the areas more vulnerable by destroying dunes and other protective natural features.

Our hazard management programs have been too narrowly focused on simple loss reduction. Programs have been carried out in a closed framework that does not embrace the larger context of how society relates to its natural environment.

The traditional perspective on hazard management is that it is cyclical: we prepare for, respond to, recover from, and attempt to mitigate vulnerability to them. Hazards tend to be viewed in and by themselves, and from a profession by profession perspective, and not an integrated one. The belief is that all mitigation and preparedness is good and that “constraints" are to blame for a lack of headway in flood mitigation. For example, we cite constraints such as pressure for economic development, the low salience of risk in the public, and a decentralized political system as reasons that our mitigation programs fail.

This way of viewing and organizing hazard management programs focuses on short-term gains instead of long-term implications, and places an artificial separation between hazard issues and other community issues. This focus tends to lead to singular solutions and technological fixes rather than integrated and interdisciplinary problem solving mechanisms that have local saliency.

IV. A NEW PARADIGM - SUSTAINABLE HAZARD MITIGATION

Disasters by Design suggests that a change in national culture will be necessary if society is ever to overcome the devastating losses from natural disasters, and that alternative ways to view these extreme environmental events are needed before any real progress in hazard management and loss reduction is made. Central to this view is a recognition that the nation cannot be made 100% disaster-proof. This also requires that somewhere, someone, somehow will have to define acceptable risk and then be willing to take responsibility for the decision of that definition. We suggest this decision making and acceptance of responsibility be undertaken throughout the nation on a community-by-community basis.

The major findings emerging from the Center's analysis suggest there is a need for a new paradigm of hazard reduction called "sustainable hazard mitigation." It is one where local citizens look forward, consciously plan, and "create" their future, rather than simply responding to the results of a lack of planning. Sustainable hazard mitigation calls for the creation of empowered stakeholder networks, embraces the notion of adjusting to the environment, incorporates a global systems perspective, embodies the concept of sustainability, and derives its moral authority from local consensus. In short, the new paradigm must go beyond simply reducing losses due to hazards to building sustainable local communities throughout the United States.

To be "sustainable" over the long term, a locale would undertake actions to reduce losses from an extreme environmental event only when those actions also: (1) maintain environmental quality, (2) maintain a certain quality of life for all residents, (3) promote disaster resiliency, (4) promote a vital local economy, (5) ensure intra- and inter-generational equity and (6) are consensus based. Activities that strengthen a community's overall social, economic, and environmental sustainability will, in most cases, also contribute to its disaster resiliency, and vice versa. Thus, working toward sustainable communities (and eventually regions, nations, and the world) goes hand in hand with working toward becoming resilient to extreme fluctuations in the climate.

Further, under this paradigm, actions to reduce losses must be based on local stakeholder consensus about the communities being designed for their great grandchildren's grandchildren. This requires that hazards experts work with local officials and others who seek different worthwhile societal goals like economic development and ecosystem preservation. It requires people to think about what life might be like in 100 years, how hazards fit into that life, and how decisions made today affect how hazards will impact life in the future rather than ignoring or simply tolerating them.

The Natural Hazards Center's report is, ultimately, suggesting that national policies regarding hazards must be integrated into a broader context before any long-term progress in reducing losses can be made. Extreme events are just one aspect of the natural environment within which they occur. In the same way, human activities that increase or decrease risk to any natural hazard are part of larger social, economic, and cultural systems. Sustainable hazard mitigation puts hazards into the wider framework of sustainable development. It calls for people to establish consensus within their communities about how they will cope with hazards, how they will use their hazard-prone lands, and how they will pay for and recover from future disasters. They would do this as one part of a process of working toward the overall goal of sustainability.

V. RECOMMENDATIONS FOR THE FUTURE

Sustainable hazard mitigation ... sounds great, but can it be implemented? To begin with, it is useful to think of disaster resiliency as a specific aspect of a sustainable community.

Resiliency is the quality of being able to "bounce back" fairly quickly from an extreme natural event without permanent, intolerable damage to or disruption of natural, economic, or structural systems. It also means that the community can do this without massive amounts of outside assistance.

The shift to a sustainable approach to hazard mitigation will require a shift in the nations' culture. The Center's project offers several recommendations for actions to achieve sustainable hazard mitigation and resiliency.

a. Build local networks, capability, and consensus. Hazard specialists, emergency planners, resource managers, community planners, and other local stakeholders seek to solve problems on their own. An approach is needed to forge local consensus about disaster resiliency and nurture it through the complex challenges of planning and implementation.

One potential approach is a "sustainable hazard mitigation network" in each of the nation's local communities that would engage in collaborative problem solving. Each network would produce an integrated, comprehensive plan linking land-use, environmental, social, and economic goals. An effective plan would also identify hazards, estimate potential losses, and assess the region's capacity to deal with those hazards. The stakeholder network especially needs to determine the amount and kind of damage that those who experience disasters can bear. These plans would enable policymakers, businesses, and residents to understand the limitations of their region and work together to address them. Full consensus may never be reached, but the process is essential because it can generate ideas and foster the sense of community required to mitigate hazards.

This kind of holistic approach will also situate hazard mitigation in the context of other community goals that, historically, have worked against action to reduce hazards. Finally, the process will advance the idea that each locality controls the character of its disasters, forcing stakeholders to take responsibility for environmental hazards and resources and realize that the decisions they make today will determine future losses.

b. Establish a holistic government framework. To facilitate sustainable mitigation, all policies and programs related to hazards and sustainability should be integrated and consistent. One way to move toward this end would be to conduct a conference or series of conferences to enable federal, state, county, and city officials to reexamine the statutory and regulatory foundations of hazard mitigation and preparedness in light of the principles of sustainable mitigation. Potential changes include limiting the subsidization of risk, making better use of incentives, fostering collaboration among public agencies, nongovernmental organizations, and the private sector, and setting a federal policy for guiding land use.

c. Build data bases and decision making tools. Initially, because communities should not be asked to make decisions in the dark, there is a need to provide them better information and decision making tools. They should have up-to-date scientific information at their disposal, as well as guidelines regarding how to proceed.

To begin with, some fairly significant data needs to be gathered. A national risk assessment (of physical systems, social systems, and the built environment) must be conducted at a scale that is useful at the local level. For example, in the United States, while most communities already have access to maps which show the location of flood prone areas in their vicinity, most of them do not have information regarding the number of buildings or the size of the population that reside in those areas. Further, even less information is available on the level of vulnerability of these buildings (e.g., the relationship of a structure's lowest floor to expected flood levels) and of these citizens (e.g., the extent to which they are insured against flood losses).

In addition to the basic information described above, decision support systems must be provided to local stakeholders that not only estimate loss based on today's situation but that also project: (a) alternative levels of vulnerability based on future population growth and other factors, (b) losses in future disasters based on alternative mitigation decisions made today, such as different land use and building code decisions, and (c) impacts on and changes in other aspects of sustainability like environmental quality, economic vitality, and social equity. The systems need to enable network decision makers to "see" the community-of-the-future consequences of every decision they make today.

d. Provide comprehensive education and training. Today hazards managers are being called upon to do things that they have never been asked to do before, for example, to make sense of complex physical and social systems, conduct sophisticated cost-benefit analyses, and offer long-term solutions. Consequently, education for hazard mitigation and preparedness should be expanded into interdisciplinary and holistic degree programs. Members of the higher education community will have to invent university-based programs that move away from traditional disciplines toward interdisciplinary education to solve real world problems in linking hazards and sustainability.

e. Measure progress. Baselines for measuring sustainability should be established now so that future progress can be measured. Interim goals for mitigation and other aspects of managing hazards should be set and progress in reaching those goals regularly evaluated. This effort will require determining how to apply criteria such as disaster resiliency, environmental quality, intra- and inter-generational equity, quality of life, and economic vitality to the plans and programs of local communities.

Also, both Canada and the U.S. currently have several different programs in place that are meant to contribute to the nations' disaster resiliency at the local level. Seldom, however, are such programs evaluated to assess what the results of those programs are on the ground. Local, State, Provincial, and Federal policy makers alike really have no empirical data on which to make judgments about whether programs designed to reduce losses actually achieve that goal, much less what those programs' effects are on the other aspects of sustainability. With good evaluations, programs could be adjusted (or discarded) as appropriate. In the process, lessons can be learned and advice given to the local level. At the same time, local communities should evaluate their own programs, so they may give the federal government advice on what kind of assistance would be most beneficial to them. Thus, evaluation and change at both levels, and interaction between the levels, will strengthen both local and federal programs.

Promoting this new "culture" will be a delicate dance between all levels of government, the private sector, and other organizations, as well as political and moral convictions. Promoting sustainable hazard mitigation should mean more than developing a plan and delivering it to communities. The questions will be difficult, the answers will be harder, the recommendations will not be easy to implement, and the process will be long. In fact right now the proposed changes do not seem possible. But there was a time in this country when it didn't seem possible that people of different races could drink out of the same water fountain and there was a time when smokers who got lung cancer were considered unlucky; now we think of them as victims of an addiction promoted by powerful and seductive economic interests. We believe a similar cultural shift is possible in regard to the way we relate to the natural environment and suggest the steps recommended above as the first way to go in achieving that shift.

Climatic Extremes and Water: Policy and Operations

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"Uncertainty is not the hallmark of bad science, it is the hallmark of honest science…….This perennial question "Do we know enough to act?"- is inherently a policy question not a scientific one" (Hon. George Brown, 1997)

There are four general issues within water management in the United States, which can produce critical conditions for planners, decision-makers, and managers. They are (1) large-scale inter-basin transfers; (2) quantification of Native American water rights, (3) an energy crisis, and, (4) extreme climatic events e.g. drought and floods (see White, 1986). These are sensitive to and exacerbate ongoing social dynamics of increasing population and consumption, deteriorating water quality, environmental water allocation, ground-water overdraft, aging urban water infrastructures, variations in state laws and, the changing nature of Federal, State, Tribal, and local interaction (see WWPAC, 1998). The result has been an almost total lack of regional capacity to implement plans relating to the impacts of environmental variability and change.

Extreme events are the chief driver of water resources system adjustments to environmental and social change (Riebsame, 1993). How well water systems handle the extreme tails of current or altered climate distributions is likely to be an overriding concern as systems become more constrained. The behavioral problem is that resource managers have difficulty anticipating how complex systems will respond to environmental stresses. In addition it can be very difficult to know which part of an anticipated decision to act on. Many disasters (or near) result from the extremes superimposed on antecedent cumulative conditions ranging from a few months to decades prior to their occurrence (Pulwarty and Melis, 1999).

Water management, if defined as the provision of water for large-scale agricultural, energy and consumption, has been a story of success. As demands for water have changed and expanded, the costs of developing additional water sources through supply-side solutions have become both prohibitively expensive and in some cases socially unacceptable. Most large river systems in the U.S. (e.g. the Colorado) exhibit the characteristics of a "closed or closing" water system (Peabody , 1991, see Table 1 and 2). In such systems management of interdependence becomes a public function, development of mechanisms to get resource users to acknowledge interdependence and to engage in negotiations and binding agreements become necessary, and, implementation of such mechanisms does not appear to be viable without focusing events. Focusing events, precipitated by the occurrence of extremes, are usually associated with exceptional societal or environmental impacts which highlight critically vulnerable conditions (e.g. 1983 flooding on the Colorado, 1993 flooding on the Mississippi, the drought of 1988).

Under these conditions, decisions that bring rigidity to the management system ultimately generate more problems than they resolve (see cases cited in Glantz, 1988 and Gunderson et al., 1994). As these trends evolve, extreme-event impacts research and applications are expected to assume greater immediacy with emphases including impacts in urban areas**,** the public sector; scheduling, operations, and performance of various private sector activities, and assessment of users (Changnon, 1995).

Water and Management: Availability and Use

The key components of water management are supply management and augmentation, demand management and allocation, and the resulting environmental concerns. The nine western water regions identified by the USGS (excluding Alaska and Hawaii) account for 90% of the total (surface and ground) water withdrawn for irrigation and almost half of the total freshwater withdrawals in the U.S. These are determined by water quantity, quality, timing and, location. About 47% of all dams and 55% of total storage in the U.S. occur in the 17 western states (Frederick, 1990). While data on sedimentation rates for most dams are limited, Elephant Butte Dam on the Rio Grande has lost 25% of its capacity since being built in 1916.

Demographic, institutional, and climatic variations and changes can disrupt existing relationships and current wisdom about society-environment interactions. A recent study by the consortium of western water resources institutes (the Powell Consortium) has shown that while the Lower Colorado River Basin is indeed drier than the Upper Basin, it is the Upper Basin that is vulnerable to severe, long-term drought. This is because of the legal requirement made early in the century (1922, 1928) to meet the Lower Basin and Mexican Treaty agreements (8.25 maf water/yr) before meeting its own needs. Interestingly, as part of New Mexico's allocation about 110 000 af of water a year now flows from the Colorado Basin to the Rio Grande Basin through an inter-basin transfer, the San-Juan Chama Project, completed in 1974. As with many other large western rivers there is, at present, no single decision-making body that encompasses the entire basin.

Substantial variations also exists among the states in the application of the "appropriation doctrine" water law. For instance a major difference between Colorado and New Mexico is that the latter state closes claims on surface and groundwater when total claims approach some "safe yield". This means that New Mexico has fewer but more reliable water rights with consequent impacts on economic development and the ease of water administration. Utah, in particular, protects public non-market values generated by water (instream flows, habitat, fisheries, recreation) in the establishment and transfer of water rights. Colorado protects only other water users. Thus, Colorado stream systems may be under greater stress than Utah and New Mexico. Thus laws, regulations, systems design, operational inflexibility, and legal, institutional and scientific constraints can reduce the adaptability of water systems to respond to climatic variations and system extremes. More importantly, recent recognition has been to the fact that effective management is required across several time and space scales (Table 3). Socially responsible decisions require broad public participation channeled through appropriate institutions and agencies and employing the best available scientific information (see Howe, 1997).

Vulnerability

Extremes result in disasters when they exceed organizational capacity to respond effectively. Preliminary estimates of vulnerability to weather extremes and climate conditions in the major river basins of the U.S. indicate that thresholds have been reached in the areas of storage and consumptive depletion vs. renewable supply, increasing dependence on hydroelectric power, high streamflow variability and, increasing groundwater overdrafts exacerbated during periods of reduced surface flow (Gleick, 1990). The U.S. Bureau of Reclamation has indicated that during a dry period such as occurred from 1931-40 the water needs of the lower Colorado River Basin would not be met. A repeat of such an event would also have significant impacts on both the Missouri and Rio Grande Basins. For instance, one study showed that hydropower production and reservoir storage would decline to about half their present values under 1931-1940 conditions (see Frederick, 1991). The flow of the Missouri River during the 1988-1989 drought exceeded that in the 1931-1940 period by about 20%. Four out of the five costliest weather-related disasters between 1980-1997, excluding hurricane impacts, occurred within the basins of western states. Each exceeded $1 billion in damages and costs, with the recent 1996 drought in Texas reaching $5 b. Even in the water-rich Pacific Northwest region trade-offs between hydropower, irrigation and salmon requirements have brought allocation systems to their limits, threatening the very sense of community and reducing the likelihood of water transfers to drier regions.

While water banking and inter-basin transfers have been used to mitigate the effects of short-term drought, the maintenance of supply during periods of severe long-term droughts of 10 years to 100 years (the timescales of project implementation and ecosystem management efforts), known to have occurred in the West over the past 1000 years, is as yet untested. The spatial extent and persistence of drought may produce shortages not only in the locale considered but also in neighboring regions that otherwise are supposed to make surplus water available for inter-basin transfers. On the other hand the transformation of the Red River in North Dakota in the spring of 1997 provides a recent reminder of what can happen when too much water arrives in too short a time. Increases in flood and drought variability would require a re-examination of emergency design assumptions, operating rules, system optimization, and contingency measures for existing and planned water management systems (Stakhiv, 1993).

The conditioning factors on present and future water resources management in the West has been summarized as follows: increasing population and consumption, uncertain reserved water rights (in particular quantification of Native American rights), increasing transfer of water rights to cities, deteriorating water quality, environmental water allocation, ground-water overdraft, outmoded institutions, aging urban water infrastructures, and the changing nature of federal, state and local interaction (OTA, 1993). As demands for water have changed and expanded, the costs of developing additional water sources through large-scale structural solutions have become both prohibitively expensive and socially unacceptable. Increasing costs of water supply projects are inevitable because, (1) the best reservoir sites have already been developed, (2) as storage capacity on a stream increases, the quantity of water that can be supplied with a high degree of probability only grows at a diminishing rate, and (3) rising opportunity cost of storing and diverting water as society places higher values on instream flows (Frederick, 1991). The limited opportunities for increasing freshwater supplies suggest that demand management will play an increasing role in balancing the demand-supply relationship and determining the overall benefits derived.

Mitigation measures undertaken by Federal and State agencies include: improvements in streamflow and demand forecasting improvements, water transfers and re-allocation, use of advance decision support systems, development of drought indicators, conjunctive groundwater/surface water use, monitoring of water supply and distribution, use of wetlands for storage, recharge and wildlife enhancement, water-use efficiency practices and, public information communication and coordination. The sectors and stakeholders include instream and withdrawal uses affected in each region are (1) water rights holders (2) agriculture (including business and farmers in area of origin), (3) hydropower, (4) the environment (including instream flows and water quality), (5) urban interests (6) Indian tribes and (7) non-agricultural rural areas. A major component of studies should thus lie in understanding the nature of vulnerability of downstream semi-arid regions to variability in the moisture-rich upper basins.

Framing: Policy and Operations

"If you have a hammer everything looks like a nail (but usually turns out to be a thumb)"

A fundamental axiom of the policy sciences is that policy is made not by a single decision or a unitary decision maker but by a multistage process in which contending interest groups or stakeholders attempt to advance or to protect their interests, preferences and, problem frames (Healy and Ascher, 1996). The concept of "framing" has emerged from work in sociology, geography, anthropology, communications, business management, science studies, and in the policy sciences. Framing is related to the organization of knowledge that people have about their world in the light of their underlying attitudes toward key social values (e.g. nature, peace, freedom), their notions of agency and responsibility (e.g. individual autonomy, corporate responsibility) and their judgments about reliability, relevance, and weight of competing knowledge claims (Jasanoff and Wynne, 1997). Researchers, policy-makers and practitioners (public and private) operate on different time-lines, use different languages, and respond to different incentive systems (Table 4). "Operations" are taken here to mean activities and decisions that take place on a day-to-day basis. There are thus, a plurality of contending legitimate perspectives, which must be interpreted and secured (Table 5). For instance from a research perspective, detectability as evidence of changes arguably requires a high level of confidence. However, if a change is believed to be occurring then a lower level of significance may suffice since what is being sought is useful advice on consequences (Pittock, 1999). As pointed out by the former Chairman of the U.S. House of Representative Committee on Science and Technology, requirements for unrealistic levels of scientific certainty must not be a roadblock to the justification of sensible precautionary actions (Brown, 1997). In a practical setting, concepts, models, theories etc. are viable only if they prove adequate in the context in which they are being applied (Lasswell, 1971). These frames lead to different definitions of what constitutes the critical components of a problem, different approaches to problem-solving, to decidedly different recommendations for action, and to differing criteria for appraisal

Information Needs and Research Approaches: Improving efficiency, quality and, equity

From a resource management standpoint assessments are needed on present and future availability of water, present and future demand and on consequences on the environment (see Frederick and Gleick 1999). The overall goal from the scientific viewpoint here is to improve predictions on the time and space scales and on variables (see Table 6) that are most relevant to the management of water resource at urban-rural interfaces and those appropriate to understanding hydrologic variability of surface and ground water basins. There is strong need to distinguish between FIRST ORDER impacts of climatic change (precipitation, changes in runoff, infiltration etc) from HIGHER ORDER or SYSTEMIC impacts akin to water resources management (see Stakhiv, 1998)

As Stakhiv (1996) points out, the measures implemented by California during the 1987-92 drought are the same measures offered for adaptation to climate change. He argues that society is continuously adapting to the combined forces of climate variability and shifting demands. The present difficulty in meeting environmental needs and mitigating against third party impacts would however indicate that the claim may be premature.

Scientists are called in to address competing demands on freshwater and dependent ecosystems, but they are increasingly unable to respond at scales commensurate with the issues, particularly because of a lack of a socio-environmental perspective needed for understanding, protecting and managing the regions water. The framework advocated here builds on the lessons learned from adaptive management, drought response action plans and, watershed-scale initiatives developed in the West. It takes an approach that is problem-oriented, contextual and, multi-method.

The research goals are to identify, (1) critical water-related problems, (2) social and economic trends altering demands and influencing the degree of vulnerability of system outputs (agriculture, recreation, power, water quality) to extremes of climate variations and to sequences of events, (3) lessons from past events and measures to increase the flexibility of water allocation among users in response to interannual variability and longer-term trends, (4) the types of information that scientists can and should produce to substantiate environmental change and, (5) entry points for the application of scientific information in mitigation measures employed by water managers and decision-makers. By "applications" is meant the transformation and communication of relevant research, including forecasts, to meet specific needs of decision-makers in the public and private sectors, and the development of capacity needed to facilitate this process (Crowley et al., 1995). This includes input to innovative procedures, such as adaptive management, for balancing new demands on instream water, such as river-based recreation and endangered species flow requirements, with traditional uses (Pulwarty and Redmond, 1997).

Seasonal forecasts of snow pack and streamflow play significant roles in meeting management needs, described above. The two factors most often used for Spring streamflow forecasts prior to the Spring runoff period are: (1) April 1 snowpack conditions, i.e. accumulated over the winter-season months(December through March), and including snow-water-equivalent, and, (2) antecedent conditions as indicators of soil moisture (water retention capacity. The climate-related parameters that govern forecasts issued monthly and updated every two week during the main Spring runoff period (April through July) are: (1) the variability and extremes of precipitation since the end of the normal accumulation season (April 1) and, (2) the historical timing of Spring snowmelt and its magnitude and duration including snowpack-runoff relationships. Recent research on coupled forecast-decisions systems on these time-scales (see Georgakakos et al 1998) has indicated much promise for the mitigation of adverse effects of climatic forcing on regional resources.

Adaptive Management and Information Communication

One promising approach has been employed throughout the course of history but not always in a deliberate fashion. As pointed out by Frederick and Gleick (1999) "The socio-economic implications of both climate and non-climate impacts on supply and demand for water will depend in large part on the ability of water-management systems to adapt to change and to eliminate current inefficiencies in managing and allocating the resource" . Adaptive Assessment and Management , including adaptive management (Walters and Holling, 1990), is an approach to natural resource policy decisions that embodies a straightforward imperative: actions that arise from policies are experiments that should be designed to produce usable lessons (Lee, 1993; Walters, 1997). One major aim is to increase the flexibility of any system or population to adapt to or recover from (i.e. exercise resilience) unforeseen consequences or "surprises." The concept of adaptive management (AM) is based on the recognized need for operational flexibility to respond to future monitoring and research findings and to varying environmental and resource conditions over the long term. Actions taken in this approach must be, by definition, from an integrated resources perspective where learning is actively pursued. The key principles of operation for AM to occur are:

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

The gap between conceptual feasibility and practical implementation is immense. "What strategies should water managers pursue in formulating programs for flood and drought mitigation under climate uncertainty?" (Stakhiv, 1998). One of Gilbert White's (1966) most important contributions to understanding decision-making about environmental hazards was in developing a framework for structuring the analysis of adjustment decisions. He distinguished between the theoretical and practical ranges of choices. The physical environment at a given stage of technology sets the theoretical range of choice open to any resource manager. The practical range of choice is set by culture and institutions, which permit, prohibit, or discourage a given choice. As argued in this paper, an avenue for integration between these two frames may lie in collaborative explorations of information communication and use. While there has been increasing focus on the processes by which knowledge has been produced less time has been spent examining the capacity of audiences to critically assess knowledge claims made by others for their reliability and relevance to those communities (Fischoff, 1996). The ability of practitioners themselves to manipulate data and to reconcile scientific claims with their own knowledge play important roles in their choices. The barriers to climate information acceptability and use reflect combinations of technical, cognitive, financial, institutional , and cultural conditions that influence the processes of information generation , content, dissemination, communication, utilization and evaluation (Tables 7 and 8). As is hopefully evident from this review, moving beyond the commonly held assumptions of climate information dissemination as a one-way (or even two-way) linear communication from researchers to practitioners requires a mix of problem-solving and interactionist approaches. This review illustrates the need for (1) reframing questions from the points of view of those affected in addition to specifying the physical risks (2) for carrying out small scale reversible innovations designed for learning, and (3) making water systems less vulnerable to present variations and more adaptable to future changes.. The goal is to field test multiple discrete alternatives, under non-crisis situations, that can be implemented when responses are needed.

Generally, in respect to climate extremes and water resources we can conclude:

1. Water resource systems are in a state of constant adaptation and most water systems are already "managed"

2. Future impacts may be larger (than at present) from cumulative smaller-scale events because of demographic and economic changes, and habitat loss). Precise definitions of future physical effects and socio-economic impacts of weather and climate extremes may be impossible to determine (see Changnon, 1998). Some sensitivities are well known but are changing in time.

3. There needs to be greater focus on high probability low impact events that have incremental and cumulative effects as well as low probability, high impacts events

4. Major changes are occurring in the roles of federal, state and local entities. What this means in the light of calls for "integrated", "watershed" or "systems-based" approaches needs to be a focus of inquiry

5. Expansion of the "beneficial use" concept in the Western U.S. should include all instream

uses and regulatory changes should allow any party to hold water rights for these broader beneficial uses especially relevant during times of drought (Howe, 1997). In addition adequate and efficient forms of compensation to basins of origin when large out-of-basin transfers occur are needed.

7. There is a strong need for the inquiry into and development of interactive approaches between decisive (operations) and non-decisive (research) participants to take advantage of new opportunities as systems evolves. This interaction is should focus on an understanding of problem definition, framing, and symmetric learning between the two groups or among individuals within them.

8. There is a need to evaluate and understand the successful adaptations in the context in which they occur. This includes explicit examination as to why some expected outcomes are not occurring in spite of "best available knowledge" (e.g. Pacific Northwest wild salmon recovery programs).

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Table 1. The Colorado River (hypothesized) severe sustained drought study (see Lord et al., 1995)

1. non-consumptive water uses are highly vulnerable to drought

2. consumptive uses are well-protected

3. drought risk is greatest in the Upper Basin

4. the Lower Basin suffers from chronic water shortage but bears little drought risk

5. opportunities exit for win-win situations and rule-changes

6. that such rule changes are extremely difficult to make

7. that intrastate drought management is very effective in reducing potential damages

Table 2. Lessons from the multi-year (1987-1992) California drought

a. water transfers will continue to play an important role in meeting water needs in California

b. impacts to the local economy of source areas (third-party impacts) are real but hard to quantify

c. it is essential that water transfers be made on the amount of "real" water available for transfer, cognizant of the physical connections between ground and surface water

d. public policy on transfers is evolving and will need to continue to change

e. greater state assistance is needed for non-bank water transfers

f. drought motivates exploration and change

Table 3. Examples of cross-scale issues in river management on the Colorado River

Temporal scales

Indeterminate: Flows necessary to protect endangered species
Long-term: Inter-basin allocations and those allocations among basin states
Decade: Upper Basin delivery obligations, life-cycle of humpback chub (*Gila cypha*)
Year: Lake Powell fill obligations to achieve equalization with Lake Mead storage
Seasonal: peak heating and cooling months
Daily-monthly: Flood control operations, Kanab ambersnail impacts
Hourly: Western Area Power Administration's power generation decisions

Spatial scales

Global- Climate influences, Grand Canyon National Park World Heritage Site
National-Western water development: irrigation, Grand Canyon Protection Act (1992)
Regional-Prior appropriation, Upper Colorado River Commission, Upper and Lower Basin Agreements, energy grid
State-Different agreements on water marketing within and out-of-state, Water Districts
Municipal--community- household

Table 4. Summary of problem definition frames of major groups in the Columbia River Basin involved in salmon management

Conservation:	Continuing pressure for use of resources led to salmon decline. Focus on habitat issues for wild fish and likelihood of barging
Habitat management	Restore fisheries to harvestable levels. Drought exacerbates fish issues
Industry/Utilities	Generating streamflow. Shape [timing] and volume of runoff. Present situation is due to natural variations. Asked to do too much for salmon
Regulatory Agencies	Number of fish and their location for harvesting regulation. Meet the goals of the Endangered Species

Table 5a. Climate information commonly mentioned useful for river operations: Magnitude, Timing, Duration, Spatial Extent

Temperature (year to date)

Precipitation
Snowpack

Changes ENSO variability
Soil moisture/trends

Streamflow

Snowpack-runoff relationships in late Spring

Table 5b. General conditioning factors in water management

Climatological and hydrological history and setting

Economic development and land use patterns

Water management and development i.e. situation assessments

Legal and Political evolution

Ecological trends/problems: water quality

Projections of Basin-scale development

Table 6. Some factors identified as affecting the degree of climate information utilization

The nature of climate information and its development

- The impact and criticality of climate variability on issue of interest
- Identification of those impacted (positive and negative): actual and potential
- Identification of competitive applications and users

The decision characteristics, communication process and the communicator/provider experience

- Knowledge of the systems and it management: The nature of decisions and context of use (formal and informal)
- Getting the stakeholders right and getting the right stakeholders
- Identification of entry points for information

The acceptability of information and participatory implementation

- Role of the stakeholders in determining the relevance of information produced and the development of products: what is provided and what is actually being asked for?
- Capacity of practitioners to validate knowledge claims of providers
- Clear identification of benefits: Evaluation of consequences of use
- Practical opportunities for effective applications

Monitoring and continual revision of interventions

- Μεασυρεσ οφ φεεδβαχκ, ρεφινεμεντ, ιντεραχτιον οϖερ τιμε ι.ε. λεαρνινγ ανδ ιννοϖατιον αμονγ πραχτιτιονερσ, προϖιδερσ ανδ ιντερμεδιαριεσ

Table 7. Developing a practitioners' checklist

What is (are) the nature of climate-related risk(s)? How reliable are the relationships over time?

How significant are the impacts of events that are have low probabilities of occurrence?

The degree to which errors resulting from actions are irreversible.
What are the appropriate scales for action (prototype etc.)

What are the broader implications of recommendations?

To what extent do providers have direct interests in outcomes?

What are the benefits? What does having the information contribute (actually, potentially)?

What is the role of the communication process and the actors (who is an "expert" and why?)

How can relevant information be obtained?

How and where can effective participation be initiated and maintained?

How can the messages and providers be evaluated (especially in terms of overconfidence)?

What are the uncertainties, indeterminacies and how is ignorance accounted for?

Who is responsible (and accountable) for management of information?

What are the action alternatives? What are their associated costs?

United States–Canada Symposium on
North American Climate Change and Weather Extremes

Operations / Policy Perspective Discussion Paper on
Water Supplies

by Lorrie Minshall

About the Grand River Conservation Authority

The Grand River Conservation Authority is a partnership of the 40 municipalities in the Grand River Watershed for water and natural resource management on a watershed basis. The partnership was formed in 1938 in response to water quality and flooding issues. Its 26 member Board is composed of members appointed by the municipal councils in the watershed.

The Grand River Watershed

The Grand River drains an area of 7000 square kilometres in Southern Ontario, and is the largest tributary to Lake Erie on the Canadian side

Most of the basin's 800,000 residents live in the 5 cities and place high demands and stresses on the surface water resources of the central basin. The central portion of the Grand River watershed is one of the fastest growing areas in Ontario. The population in the watershed is expected to grow by 37% over the next 20 years, an increase of 300,000. 90% of the watershed is rural and is intensively farmed.

Today, the Grand River is one of the healthiest river systems in North America in a heavily populated area. The sport fish are back, and recreational use of the river has increased significantly. Many of the communities along the Grand River valley are looking to the river system as a focus for developing a viable tourism industry.

Water Issues

The Grand River watershed is the only heavily populated area in Ontario that is dependent on an inland river and groundwater system for water supply and wastewater disposal. It is also a heavily managed system that must be balanced very carefully to meet these demands.

Because of the rapid population growth, the Cities are concerned about securing long term water supply, protecting the quality of groundwater resources and surface water supplies, and dealing with their increasing wastewater.

Four multi-purpose reservoirs are operated by the Grand River Conservation Authority as a system for low flow augmentation and for flood control. The reservoirs are very important to the system, supplying up to 85% of the summer flow through Kitchener in dry summer periods.

The reservoirs have a 98% reliability of meeting flow requirements based on the last 35 years of record. In fact, the design of this entire system of reservoirs, flow targets, water withdrawals, wastewater treatment strategies and water quality objectives is based on the last 35 years of record.

Water Management

To deal with these issues, GRCA has invited together municipalities, stakeholders and government agencies to update the watershed plan. There are about 300 people directly participating in various parts of the process. The Water Managers Working Group is comprised of water/wastewater managers from the watershed's serviced communities, and other water and water quality interests. This group is developing a watershed wide water quality management plan and a water budget & water supply strategy.

The Conservation Authority's role is to provide the forum, and to consolidate and manage the data, models and technical expertise to support the development and maintenance of the plan, and the associated municipal water and wastewater plans. I am project manager for this work.

The hard work over the last three years to consolidate the data and the models needed for water planning is nearing completion. The year 2000 is the year of the plan.

The working group is currently preparing a drought contingency plan to deal with the current drought situation if it continues and worsens. This contingency plan is the forerunner of next years' planning for water supply and water quality in the face of population growth, agricultural intensification, and climate change.

Overall, the plan will address:

1. getting water use under control -- that is implementing water planning and management for sustainability, and
2. improving the resiliency of the watershed to withstand or adapt to change, which we refer to as watershed health.

Major Climate Variability and Climate Change Concerns

How are our water supplies vulnerable to climate variability and climate change?. Because of the reservoirs, the system can handle seasonal shifts in water inputs. We are prepared to make adaptive changes in our standard operating procedures as the situation arises.

The system can handle such dry years as the 1962-1966 period or a year like 1988. If, on the other hand, there are successive years of low precipitation that lower the groundwater levels, such as those that occurred in the early 1960's and are occurring now in 1997-1999, this will affect the groundwater supplies which are a part of that balance, and put more pressure on the surface water supplies. It will seriously affect the rural community, that is dependent on the groundwater system, and the natural environment that is dependent on the groundwater discharge.

Increases in water temperature that worsen the dissolved oxygen problem, even two parts per million, will upset this water quality and water supply balance, and it will also affect the diversity of fisheries habitat and the outdoor recreation opportunities.

And if there is a serious risk of significantly lower annual precipitation continuously, as was suggested by some of the early climate change scenarios, the Grand River system will not have the capacity to support its growing population, and costly water supply and management decisions will have to be made. The controversies about new reservoirs and pipelines to the Great Lakes will come around again, or, alternatively, there will have to be major changes made in the way we use water.

So now to the questions put to this discussion forum:

What is the role of weather and climate in water supply operations, planning, and policy?
Weather and climate are central to water supply operations, planning, and policy, since our source of water is precipitation, and our supply of water is dependent on the vagaries and variabilities of weather and climate.

What characteristics of extreme weather are most “important” in an operations/policy context?
Rainfall intensity, duration, areal extent and frequency are most important in an operations/policy context, whether dealing with floods or droughts.

What aspects of operations are most vulnerable to extremes?

Heavy rain causes localized flooding, particularly in urban areas. Heavy rain over a large area (several thousand square kilometers) and lasting for a day or more cause most of the devastating floods. Even worse if combined with heavy snowpack, rapid melt, or saturated soils (from a previous wet month)

Shortage of rainfall for three or more weeks in summer causes crop losses and low yields, particularly where crops are not irrigated. This situation will <u>not</u> worsen with duration unless the system is reliant on reservoirs, either man-made reservoirs, groundwater aquifers, or larger bodies of water. Then duration, or cumulative shortage, becomes more important than short-term intensity.

As rainfall shortage continues into fall and winter, reservoir systems are depleted, shallow groundwater sources are not replenished and landowners’ shallow wells go dry. The accompanying sunshine and warm temperatures, and the increased demand for water further deplete surface and groundwater sources.

In general, as rainfall shortage continues into the second and third year, the combination of low reservoir levels, low groundwater levels, decreased groundwater discharge to surface water, and rainfall shortage can combine to create a crisis in water supply.

From a policy and planning perspective, our design of flood management and water supply policies and systems is based on design events. For example, urban storm water systems are based on the 100-year storm. Floodplains are established by 100-year floods defined by storms, or in our case, the Regional Storm (the largest storm observed in the geographical area). Dams are designed to safely pass a Maximum Probable Flood. Wastewater systems are designed for a 20-year low 7-day flow. Municipal water supply systems are designed for reliable supply for 50 years of projected growth, where reliable means the system would not have failed under any conditions observed in the last 50 years.

For all of these, the period of climate data or flow record used for design is, at best, 35-40 years and sometimes as little as 20-years. That being the case, the climate variability built into the design of flood management and water supply systems is no broader than the statistical characteristics of the last 35 years of climate history – an unnerving fact if it is true that we have experienced relatively benign weather in that period. If we have been designing for much greater actual risk than we think we are, then we need to change our design standards, and the information to do this must come from the climate community.

There is currently little or no routine contingency planning for conditions worse than our design standards. The information to do this must also come from the climate community.

What changes in management practices, resource demands, or other non-climate factors (e.g. land use, population distribution, political and economic contexts) may be expected to influence the vulnerability of water supplies in North America to extreme weather?

- Population growth has little relationship to the availability of water – growth projections come first, and the planning for water supply chases down a source of water to supply the population forecast. Questions about population growth are discussed in the land use planning process.
- As the predominance of city dwellers increases, we are rapidly losing our water conservation ethic and any recognition of the variability of supply, whereas rural dwellers have lived with the natural variability of water supplies all their lives.
- Local governments and water managers want to portray a secure water supply in order to keep the industry they have and to attract new industry. It is not good business to discuss vulnerability of water supply publicly. This is a key consideration for the design of programs to

encourage local contingency planning for climate variability and change. To engage local communities in discussions about climate change, one must also be able to answer their detailed questions about what climate change will mean to them, and be able to offer solutions and choices.

- The intensification of population can make us more vulnerable as areas grow beyond the local capacity to sustain them. The infrastructure put in place to secure water supply can reduce our flexibility to adapt to variability and change in supply.
- In addition, the intensification of population can threaten what local water supplies they have – pavement reduces infiltration, groundwater can decrease in quality and become contaminated.
- The disappearance of water policy into ecosystem management policy within the senior governments in the 1990's had the desired effect of broadening water management's perspective. But water all but disappeared from the policy and political agenda. People do not understand what "ecosystem" means, and it is most often associated with wildlife. If we are serious about influencing water policy, we have to say the word water.
- Given our current inability to account for water, we do not know whether our total water use is sustainable over the long term, climate change or not. On the other hand, our increasing resolve to account for water will give us a chance to reduce our vulnerability.

How do the operations / policy community use weather or climate information?
Weather and climate information is used for real-time operations, design, planning and policy development.

Real-time operations include real-time flood forecasting, warning, and reservoir operations. The major variables are rainfall, snowpack water content and temperature.

Dams are designed to pass the Maximum Probable Flood which is based on a rain storm event. Urban stormwater management facilities are designed for 100-year storms given by Intensity-Duration-Frequency curves maintained and distributed by Environment Canada.

Floodplains are defined as the area that would be flooded by the Regional Storm, the largest storm that has occurred in the geographical area. We use the 1954 Hurricane Hazel storm transposed over our watershed. Of course, Hurricane Hazel is no longer the largest storm, having been superceded in the early 1990's by the Harrow storm.

Reservoir yield studies, flow inputs to water quality studies, and surface water supply studies have historically been based on recorded river flows 1960-1995. Now we also use continuous hydrologic modeling with historical climate data inputs to extend the flow record. There are no scenarios available for extreme droughts.

The evaporation and evapotranspiration components of data and modeling are very weak. As we start to do regional scale groundwater planning and management, and link our surface and groundwater modeling, a weaknesses of this magnitude will seriously affect our ability to predict.

What factors limit the value or utility of this information for policy or operations purposes?

1. Unstructured climate data files and rapidly changing data formats make it very time-consuming and costly to consolidate a climate input data set for hydrologic modeling and scenario testing.
2. Translating research findings into operational tools. There is a huge gap between our good research results and their practice – between researchers and practitioners. There is a need for technology transfer, for interpretation, and for partnerships between the senior governments and local water managers in the development of operational tools.
3. No analysis of extremes (that have reached the trenches). No extreme event scenarios.

What sort of weather or climate information would be most useful if it were available?

To improve our ability to plan for and deal with extreme events (regardless of what is driving them):

- Improved areal distribution of observed precipitation – accessible, gridded radar and satellite –assisted precipitation estimates. We know they are available; they need to be accessible to local water managers.
- Return period design events for large tributaries (where rainfall intensity is not the determining factor)
- Improved evaporation and evapotranspiration estimates – data,

methods, and models

- Design events and seasonal/annual scenarios which consider longer-term climate variability and associated risk. Drought scenarios (with risk attached) for contingency planning.

To improve our ability to assess impacts and develop and implement adaptive strategies:

- Maintain the climate and streamflow monitoring network. Responsibility and cost is being shoved down to the local level but the capacity at the local level to maintain the system isn't going to do the job. If the senior levels of government have an interest in seeing impact assessments and adaptation strategies developed and implemented at the local level, then they will have to play a larger role than what is seemingly being planned.
- A ready-to-use climate database available to local practitioners, with one format, and with the gaps filled in by the climate professionals. Right now every one of us has to patch the raw data, clean it up, and fill in the gaps.
- Recognition among the water management community that preparedness for climate variability may require a higher design standard than what is being used. New design standards (with risk attached). Leadership in implementing a higher standard.
- A partnership between the senior governments and the local level to implement. Decision-makers will not spend money unless they get answers to their detailed questions about specifically what will happen if they don't. It is not enough to say you will have more floods; you must say that x dykes will overtop, x million dollars' worth of damage will be done in community x, or that communities x, y, and z will have floods like their devastating 19xx flood 3 years out of 10. The local water planners can do this if they have the support and the tools.
- Tools within reach of local water planners that can be used to account for water, and answer questions about the sustainability of water use relative to supplies.

Summary

In reaching out for water to feed the growing population, we are boxing ourselves in, leaving ourselves less and less flexibility to deal with variability and change.

Systems are designed based on, at best, the last 35-years of climate history. More variability, whether based on historical variability or climate change, may need to be built into our systems, and this information must come from the climate community.

Systems are designed based on risk. Relative risk must be associated with any discussions about climate or any recommendations for design standards.

The impacts of extreme weather on North American societies are locally specific, based on physical geography, water use patterns, and recent climate history. Information most likely to influence local communities to reduce vulnerability, will be information that has been translated into the local context.

Workshop paper: A science assessment perspective on air quality information gaps and shortcomings critical to understanding the impacts of extreme weather on American and Canadian societies.

C. Olivotto

1.0 Introduction.

Increasing media, policy and scientific attention to extreme weather and geologic events worldwide is pressing scientific research to provide improved understanding and prediction of the extent (spatial, temporal and magnitude) of such events into the future. This means that current scientific tools have to be capable of moving from global to regional and local scales with comparable and adequate levels of certainty. Connections are now being made by the public, policy makers and researchers, initially in the form of unanswerable questions, between weather extremes and air quality events and impacts. Current scientific knowledge and existing scientific tools (in Canada) are not capable of responding to the questions. There is a need to establish a framework for scientifically addressing the cumulative impacts of regional air quality and weather extremes including the linkages to climate change.

The information in this paper is provided to stimulate discussion of joint research directions for air quality, climate change and weather extremes. With further expert contributions, the limited examples highlighted below can be refined and expanded to become a useful tool for the development of an integrated research framework to help guide future research. Section 2.0 provides a brief overview of the issue in the context of current Canadian science assessments and section 3.0 addresses the questions posed by the workshop convenors.

2.0 Science assessments

Air quality science and effects assessments published in Canada in the latter part of the 1990s address single pollutants with some conceptual, but minimal scientific, focus on the synergy between individual air pollutants. Even less attention is paid to possible linkages with global issues such as climate change, climate variability and weather extremes. Therefore, the identified knowledge gaps and resulting recommendations for pollutant management and for research directions to be gained from the assessments do not adequately promote conjoint air quality and climate research programs.

With the exception of the acid rain assessment, very little connection is made between air quality science and global atmospheric issues. The four assessments (acid rain 1997, NOx/VOC (ground-level ozone) 1997 and particulate and ozone effects1998/99) responded to a fixed set of policy questions designed to control unique pollution problems via remedial and preventative measures. Recent scientific findings such as the reasons behind the lack of ecosystem response to sulphur controls to manage acidification and the acknowledgment that neither ozone nor particulates have a human health effects threshold, are moving both science and management of air quality in new directions. Risk management implies the need for long term adaptive capacity, integrating a range of potential (positive and negative) impacts: the focus of acid deposition is on ecosystem effects (surface waters, soils, trees), the focus of particulates is on human morbidity and mortality, and the focus of ozone is on human health and ecosystem (natural vegetation, crops) effects.

The 1997 Canadian Acid Rain Assessment confirms that interactions between climate and acidic deposition may result in changes in some acidification effects. Higher temperatures and/or drought have resulted in dramatic and sometimes unexpected changes in physical, chemical and biological conditions and processes in lakes and streams. Drought during the 1980s in central Ontario caused oxidation of reduced catchment sulphur resulting in re-acidification or delayed recovery. Furthermore, the loss of dissolved organic carbon in lakes that accompanies acidification permits a 2- to 3-fold greater penetration of biologically harmful UV-b radiation.

The Multistakeholder NO_x/VOC Science Assessment, 1997 acknowledges that mechanisms exist now to foster the cross-assessment of emissions reduction strategies. Knowledge gaps identified in the assessment of relevance to extremes are limited to confirmation in the Phase II smog management plan that there is a need for quantification of oxidant benefits accruing from CO_2 management efforts and that the Phase III smog management plan (in development) should establish the framework for measuring mutual benefits between smog emissions controls and climate change control measures.

The particulate matter and ozone effects assessments lay the ground work for development of air quality research into adaptation mechanisms. They provide a review of the latest effects research and key results that will lead air quality management into the future. Neither pollutant has a discernible human health threshold. This means that risk management and adaptation play a significant role in future pollutant management. Risk management and adaptation mechanisms will have to be developed for a range of end points and for human health and broader ecosystem effects of the two “smog” pollutants.

Finally, a qualitative assessment co-benefits funded by the Climate Change Action Fund reinforced the need to conduct a complete assessment of net benefits that result from direct actions to reduce the accumulation of greenhouse gases (GHGs) in the atmosphere.

3.0 Addressing the questions

A. *What does the historical record show regarding the vulnerabilities of North American air quality to weather extremes?*

Synoptic weather pattern prediction is integral to understanding the mechanisms best suited to integrated weather extremes and air quality management and adaptation. Air quality is largely a regional and local issue therefore it relies on development of the capability of predictive capacity of weather and climate models to forecast regional weather variation with a high degree of certainty. For example, inter-annual meteorological variability has a major influence on ground-level ozone distribution, concentrations and frequency of episodes and extreme drought/flood regimes directly influence ecosystem acidification exposure.

Stagnating or re-circulating high pressure systems (with temperatures above 25°C) and intermittent drought/flood events are the predominant weather extremes which impact on air quality, in a variety of ways:

- entraining primary and secondary pollutants in a contained airmass;
- promoting photo-chemistry (photo-dissociation of NO_2 by sunlight is the only significant anthropogenic source of O_3 in smog);
- increasing temperatures require the use of additional fossil fuels i.e. to run cooling devises, which increases smog pollutant levels;
- human health and ecosystem effects will vary depending on duration, location and the magnitude of peak of the event;
- oxidation of reduced catchment sulphur results in re-acidification or delayed recovery;
- increasing wind-blown dust and soil made available due to drought; and,
- precipitation scavenging removing (80-90%) of the mass of particles from the atmosphere.

B. *What changes in weather patterns may be expected to have the greatest impact on air quality?*

Because air quality is essentially a regional problem, and weather patterns vary significantly between regions, impacts will vary. Poor air quality in the smog-prone regions of Canada are usually associated with the following synoptic patterns:

- SW Ontario and Quebec - slow moving, stagnating air masses, fed by flows from the south-south west associated with back- of- the- (Bermuda) high;
- Canadian Southern Atlantic - slow moving flows from the US Eastern Seaboard;
- Lower Fraser Valley of B.C. - re-circulation flows in-out of the valley and inversions (trapped air masses with no venting of pollutants).

An increase in the frequency, severity and duration of these events, in concert with temperature increase resulting from climate change, will likely significantly increase poor air quality events and associated human health and ecosystem impacts (and vice versa for a decreased number).

Increased magnitude and interstitial period of drought/flood regimes may, as noted in the response to question 1, above, facilitate oxidation of reduced catchment sulphur resulting in re-acidification or delayed recovery. Likewise, changes to the drought/flood regime will effect transport and deposition soil and dust particles.

C. What non-climate factors effect the ultimate vulnerability and adaptive capacities of air quality to extreme weather?

Risk taking versus risk bearing has a tremendous effect on communication, response and adaptation to environmental problems. If the risk-taking community is also the risk-bearing community (and perceives it themselves), it is most likely to take responsibility for managing the risk. Air quality events are manifested in an immediate and often tangible manner allowing the risk takers some understanding of the burden of impacts resulting from their actions. The connection is not as easily made between actions and risk burden for climate change: the possibility of growing pineapples in Yellowknife in 2070 does not mean as much to the risk taker as the need to limit use of the automobile today to avoid your child or grandparent being hospitalized tomorrow. Emphasizing the linkages between air quality and climate change (and severe weather) may be supportive to better understanding the need for remedial and adaptive actions to deal with both issues.

Scientists have limited understanding of chemical processes and interactions between the atmosphere, terrestrial, aquatic and biotic systems. The latter half of the 1990's has produced, at least conceptually, policy and scientific efforts toward addressing integrated global and regional ecosystem stress response.

There are minimal (research and application of) adaptation tools or mechanisms. Air quality in Canada is still largely focused on remediation and to a certain extent (when remediation is proving too difficult) prevention of further deterioration. Adaptation has not been explored on either the policy or science sides of the issue with a few exceptions. Air quality advisory and prediction programs have been implemented in the smog prone regions of Canada to support human health protection. The episodic and seasonal nature and the inter-annual variability of the (smog) air quality problem mean that without a long term predictive capability adaptive measures will be responsive rather than planned. In addition, consideration has to be given to the acute and/or chronic nature of ecosystem response to air quality impacts, which varies by receptor. Humans are capable of more immediate adaptive response to exposure than are crops or other elements of the ecosystem. The only "adaptation" measures for acid rain are the Province of Ontario experiments with liming and restocking.

We have a limited ability to manage pollutant inputs to the ecosystem. NO_x is a key (primary) emission input to all three air quality issues and despite a decade or more of effort to reduce emissions they are projected to climb over the next decade. Interactions between anthropogenic pollutants and biogenic compounds create secondary pollutants. And, despite a decade or more of reducing sulphur to manage acidification, science now reveals other (not well understood) compounds and ecosystem interactions are responsible for continued acidification.

Reactive versus planned adaptation is an issue of concern. While research into climate change, variability, and extremes is actively addressing adaptation, air quality has and continues to be addressed from a remedial action and to a lesser extent, preventative action, approach. Air quality risk is managed in a responsive rather than a planned manner. At present, the regionally implemented air quality advisory programs promote short term response to air quality impacts. A reasonable intermediate step toward addressing the adaptation issue for air quality issues is the air quality prediction program, successfully tested over the past few years on a seasonal basis in southern Atlantic Canada.

D. What are current research directions related to the impacts of extreme weather on air quality?

Researchers working on the acid rain component of the air quality issue are addressing the need to understand cumulative effects, *Schindler, 1998*. The Phase 3 Smog Management Plan is supportive of quantifying the mutual benefits from control initiatives designed to reduce smog and those designed to address global warming. There is no explicit lead in to air quality adaptation science. Some continuing qualitative work is underway, with plans for quantitative evaluation of the relative magnitude of GHG reductions on other air pollutants and their environmental and human health benefits.

E. What are areas of uncertainty or critical gaps in current understanding of the impacts of extremes on air quality and what factors contribute to these gaps and/or uncertainties?

Leadership and planning are required to direct the integration of air quality and weather extremes science tools and analysis, the integration of source controls and the integration of impacts reduction and adaptation. A number of regional and multi-national air quality science organizations exist which could be used to give thoughtful guidance on research strategies and programs to address the integration of air quality science with that of weather extremes.

Research into the current and potential future linkages and impacts between air quality and weather extremes needs to proceed at a variety of scales, from local to global. The air quality monitoring networks that have evolved over the past two decades are largely urban in nature. Addressing the linked impacts of and adaptation to weather extremes may require integrated networks, more conceptually in line with the EMAN and CORE sites evolving in Canada over the latter 1990s and are critical to data quality, availability, and consistency necessary to assess change

Extreme weather has the potential to exacerbate current projections of air quality impacts. However, air quality emission projections are at a maximum fifteen years into the future: a challenge remains as to how we merge that time frame with the climate scenarios projection periods on the scale fifty years or more. This is just one example of the multitude of temporal, spatial and magnitude ambiguities currently plaguing the linking of air quality with climate change.

Modeling, emissions and ambient data provide scientific contributions to pollutant management. They also provide the scientific tools and data for risk assessment, risk management and adaptation. At present, air quality modeling systems cover urban and regional spatial scales (40km grids capable of nesting down to 5 km). Ozone modeling time scale capacity at present is for one episode, maximum two weeks. Some research efforts are underway to run scenarios for a full ozone season, May to September. Model development for particulates is including an episodic capability as well, for regional areas within North America. Emissions data, its (lack of) quality and timely availability and limited research- level ambient data to evaluate the modeling systems are an impediment to model application. Climate models at compatible spatial and temporal scales are not yet developed for testing scenarios.

Cumulative health impacts due to air quality and weather extremes are increasingly drawing research attention. Excessive heat and cold conditions,, potential for acclimatization and additional mortality or morbidity are of interest, particularly related to the more complex or indirect climate effects and interactions (see A. J. McMichael and R. Sari Kovacs. 1998 and, Duncan, 1997). Human health and ecosystem effects science progressed during the nineties to improve our understanding of the distribution and nature of risk and contributed to new management approaches for air quality. Adding the perspective of changes or cumulative effects due to climate change, variability, and extremes is necessary. For instance, data exists on mortality and morbidity due to weather extremes (and changes in) and due to smog constituents, but not the cumulative effects. Existing and new research and the analysis of independent effects and impacts needs to be expanded to quantify (predict) the cumulative impacts. Research is also needed into the mechanisms to predict extremes linking with increased ozone effects on vegetation due to the cumulative effects of ozone (damage), drought and heat extremes.

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IMPLICATIONS OF CLIMATE CHANGE FOR AIR QUALITY IN NORTH AMERICA: NEED FOR AN INTEGRATED APPROACH

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A. LIKELY CHANGES IN AIR QUALITY UNDER ENHANCED GREENHOUSE CONDITIONS

- The historical record indicates that air quality worsens under warmer/hotter conditions, particularly for ozone (for fine-PM the record is not as clear.

- Generally and almost uniformly around the planet, the presence of high-pressure systems provides conditions that are conducive to ozone and fine-PM formation, buildup and transport.

- Sufficiently high quantities, densities and rates of manmade and natural emissions of VOC, NOx , CO, SO2, NH3 and PM(under meteorological conditions conducive to pollutant buildup and formation) result in ozone and fine-PM air pollution episodes.

- An increase in the occurrence and duration of warmer conditions affects two components of the system that governs air quality:

- 1. Higher emissions of biogenic and manmade emissions of VOC, NOx, SO2 and NH3- amounts, rates and densities of emissions increase, sometimes in surprisingly large increments for VOCs from natural and transportation sources(other emission categories have not been quantitatively examined).

  2. A warmer atmosphere may not always lead to the presence of more conducive conditions for ozone because factors such as mixing , mixing depth, wind speed, UV intensity and water vapor, for example, are individually important but collectively may not result in an atmosphere that is more "reactive'. Furthermore, whether changes in such factors, either individually or collectively, result in more or less conducive conditions depends on whether and to what extent the area that produces the emissions is VOC-or NOx-limited.

E. So, warmer than average weather means more emissions, which may be emitted into an atmosphere that's more or less conducive to air pollutant formation and buildup.

- Since the mid-1980s, the occurrence of more and longer periods of above –average warm days probably may have reduced the effectiveness of federal ozone control initiatives and of state-implemented air quality improvement programs.

- However, the record shows that on average, unhealthy levels of ozone are most likely to occur under warmer than average conditions. Some regions, such as the

U.S. Midwest, Northeast, and West, seem more sensitive to these warmer- than- average conditions than do areas in the South and Southeast for reasons that are unknown to us. Analyses of PM and weather-related variables are less definitive except that generally fine-PM levels are higher during summertime and high relative humidity.

II. RESEARCH NEEDED FOR BETTER UNDERSTANDING OF INTERACTION BETWEEN CLIMATE CHANGE AND AIR QUALITY

Research to date has shown that:

- In VOC-limited regions, more ozone tended to be formed earlier in the day, due mainly to assumed constant relative humidity (leading to more water vapor at the higher temperatures and/or to higher VOC emissions).

- In NOx-limited regions, similar or even less ozone tended to be formed, but what is formed, occurs earlier in the day, which usually suggests greater population exposure.

- Air quality improvement strategies that move a region from VOC-limited to NOx-limited conditions appear to mitigate the adverse impacts of increased warming conditions on ozone concentrations.

- If the occurrence of global warming coincides with stratospheric ozone depletion (i.e. increased UV radiation), then the effects on ozone formation are additive and may be synergistic. The same may be said about the effect of this coincidence on fine-PM but the uncertainty in such a statement is large.

- New work is needed to merge the impacts of climate change with updated models of ozone and PM formation and of emissions of VOC, NOx and NH3. It would be useful if climate model outputs could provide changes in the key variables of air quality modelers and planners to have information about the expected change in frequency, duration and geophysical scope of high pressure conditions under increasing GHG emissions and to test the assumptions of constant relative humidity.

III.NEED FOR READY PUBLIC ACCESS TO AIR QUALITY MONITORING DATA AND COORDINATED STRATEGIES FOR CLIMATE AND AIR QUALITY PROTECTION

- Fossil fuel combustion causes both greenhouse emissions and air pollution; many actions that will reduce emissions that cause air pollution will cut greenhouse emissions.

- Climate change is often perceived as a distant challenge affecting future generations; air pollution, on the other hand, is a threat here and now for which it is possible to summon political resolve to reduce it once the public is well informed about how to address it.

- Policies which limit greenhouse emissions may produce large reductions in air pollution mortality. Davis et al in Lancet (1997) project 8 million particulate-caused air pollution deaths worldwide could be averted through moderate greenhouse emission limitation policies.

- Actions to reduce fossil fuel burning on air quality grounds will benefit the global climate and future generations without raising North –South or intergenerational issues.

D. Public awareness of air pollution and ultraviolet radiation levels and risks can be crucial in building support for changes in energy use and transportation policy. A particularly good model is that in Mexico City maintained by a Mexican NGO, SIMA. Mexico City air quality and UV data is on line at: http://www.sima.com.mx/ by city quadrant in Spanish and English. This system could readily be expanded to most large Western Hemisphere cities with data accessible in Spanish, English, French and Portuguese.

- Even before this data became available the NGO that set up SIMA, Instituto Autonomo de Investigaciones Ecologicas, had run a pioneering environmental awareness effort in conjunction with the city’s leading radio station. A mobile testing van staffed by chemists traversed Mexico City neighborhoods each day taking air and water quality samples and broadcasting results in regular reports over the radio.

C. The recent study by STAPPA/ALAPCO (the U.S. air quality directors ‘ groups) of harmonized strategies for climate and air quality protection indicates that these goals can be simultaneously pursued. Such a strategy can avoid piecemeal regulation and yield more effective overall results . Mexico City, in developing its air quality plans for 2000 to 2010, is seeking to achieve both climate and air quality protection. This may be an appropriate test area for such a harmonized strategy.

Extended Abstract for

High Performance Computing Architecture
And
Trends In Performance-per-unit of Cost

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The Primary Role of High Performance Computers

High performance computers enable scientists to solve problems that are not solvable with any other class of equipment. Using them, scientists can treat complexity that is otherwise intractable, reach beyond experiment, overcome the constraints of real time, etc. For example, analysis of structures in aerospace and automotive design involves treatment of very complex structures as various loads and stresses are applied. Some phenomena such as atmospheric circulation about a sphere are difficult to study experimentally. Climate change spans decades, even centuries, so it is difficult to study experimentally due to time constraints. Numerical simulation combined with high performance computers enable scientists not only to study such phenomena, but to also obtain detailed information about them in space and time and do so at affordable cost.

Trends in High Performance Computer Architecture

The desire of scientists to expand the set of solvable problems produces a constant need for more powerful computers. Problems of current interest require computers that can sustain trillions of arithmetic operations per second (Teraflops). That level of performance requires hundreds and, perhaps, thousands of processors working in parallel.

Parallel processing was not readily feasible until the advent of Parallel Vector Processing (PVP) systems in the 1980's, e.g. the Cray X-MP/4. PVPs are members of a broader class of parallel computers known as Symmetric MultiProcessor (SMP) systems. SMPs have multiple processors that run under a single operating system and that share a common memory. Each processor has uniform (or near uniform) access time to memory and to all devices, thus they are "symmetrical" with respect to memory and device access [2].

The requirement that all processors have uniform access to memory greatly limits the number of processors that can be integrated into a SMP, i.e. most SMPs can have a maximum of 32 processors. Distributed Shared Memory (DSM) systems overcome this constraint by providing the shared memory abstraction with memories that are physically distributed, i.e. attached to individual processors. DSMs also run a single copy of the operating system and may contain hundreds of processors. However, memory access time varies with respect to location of data relative to the requesting processor; so to achieve acceptable performance, programs running in each processor must <u>not</u> make frequent references to data held in memories of other processors. Providing the shared memory abstraction requires coherency between processor caches, thus DSMs are also called Cache-coherent Non-uniform Memory Access (ccNUMA) systems as well as "Virtual Shared Memory" systems. The single operating system and the NUMA cache directory make possible a single address space across all processors in the system.

As the number of processors in a single system grows, the hardware for managing concurrent memory activity must be scaled and this eventually leads to performance problems. Also, the single operating system becomes a bottleneck as the number of processors increases. Thus, to get to thousands of processors and to Teraflops performance [1]

> "The trend today in high-speed computing architecture is to cluster numerous shared memory systems … Each shared memory system in a cluster is called a 'node' which, in reality, is a computer in itself, complete with its own I/O and may contain anywhere from tens to hundreds of processors."

Message passing between the nodes is mandatory, thus this is called a Distributed Message Passing (DMP) architecture [2]. Like ccNUMA systems, achieving acceptable performance on a DMP requires that models be partitioned across the nodes so that most references to data take place in the same node. Because each node is a complete computer, there are no inherent architectural limitations to scalability. The programming model is usually some form of multitasking within a node and message passing between nodes although message passing can be used exclusively. The nodes are "commodity" systems that may be either SMP systems or DSM systems,

Trends in Sustained Performance per unit of Cost

Moore's Law states that the number of transistors per unit of area doubles every eighteen months. Microprocessor performance per unit of cost also follows Moore's Law in that performance per unit of cost is doubling every 18 months or quadrupling every three years. So we combine Moore's Law with sustained performance of clusters to project sustained performance per unit of cost during the next decade.

The efficiency of clusters (ratio of sustained performance to peak performance) typically ranges from 5% to 15% depending on the nature of the workload. The DOE NERSC at Lawrence Berkeley Laboratory recently completed a five year contract with IBM that will lead to a 3 Teraflops peak DMP at NERSC by the end of 2000 at a cost of $35M [3]. That system will have 152 nodes and each node will be a 16 processor SMP giving a total of 2048 processors. To first order, this system will provide ~85 Gigaflops peak per million dollars. At 5-15% efficiency, this gives

4.25-12.75 Gflops sustained per million dollars of cost by end of 2000.

Performance per unit of cost doubles every 18 months, so DMP clusters of microprocessor systems will

Sustain 8.5-25.5 Gflops per million dollars of cost by mid-2002.

Again, this conclusion is predicated on the assumption that DMPs will sustain is 5-15% of peak performance. However, as noted in the February, 1999, report from the President’s Information Technology Advisory Committee (PITAC):

Section 3.3 -- High End Computing

> “The vector-architecture-based sector. Currently, it is not known whether all vector-architecture applications, some of which are critically important to selected Federal missions, can be efficiently executed on high-end commodity processor-based parallel systems.”
>
> Section 3.3.2 Recommendation: Fund Research into Innovative Computing Technologies and Architectures.
>
> “There is evidence that current scalable parallel architectures may not be well suited for all applications, especially where the computations' memory address references are highly irregular or where huge quantities of data must be transferred from memory to support the calculation. To address these limitations, we need substantive research on the design of memory hierarchies that reduce or hide access latencies while they deliver the memory bandwidths required by current and future applications."

So the above trend in performance-per-unit-of-cost is predicated on the assumption that vendors will provide clusters of commodity systems that have sufficiently large bandwidth and small latency between processors and memory to sustain performance that is 5-15% of peak performance.

Summary

Simulation is the third leg of science – an equal partner with theory and experimentation. Simulation combined with high performance computers enables scientists to treat complexity that is otherwise intractable, reach beyond experiment, overcome the constraints of real time, etc. Further, numerical simulation combined with high performance computers enables scientists obtain detailed information in space and time at affordable cost.

Problems of current interest require computers that can sustain trillions of arithmetic operations per second (Teraflops). That level of performance requires hundreds and, perhaps, thousands of processors working in parallel. Thus, the trend today in high-speed computing architecture is to cluster numerous shared memory systems. Projections based on Moore’s Law indicate that, in the 2003-2005 timeframe, high performance computing centers around the world will be able to afford systems that can sustain one or more Teraflops.

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