Improved Decisions Through Climate Research, Consulting and Interpretation

CANADIAN INSTITUTE FOR CLIMATE STUDIES

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Rapid Climate Transitions

by Rick Lee, Manager Product Development

Climate has many time – and space-scales ranging from temporary shifts of a decade or two (for instance the dust-bowl years in the 1930's in North America) to the Little Ice age which lasted about 200 years. Other examples of climate 'states' are the 'Climatic Optimum' which lasted 2000 years and the Ice Age which lasted 2,000,000 years. Change from one 'state' to another – climate change – has until fairly recently, been held to be a fairly gradual process. It has been thought of as one in which subtle changes in temperatures or precipitation occur over a long period of time, centuries and millenniums, rather than decades.

Significant climate change has always had a major impact on earth's population and its geography. Development of civilization has been linked to optimum climatic conditions; agricultural lands around major river systems are impacted by changes in the precipitation and temperature regime –

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From the Chair of the Board

I am delighted to have been asked to Chair the Board. As many of you may know, my work has revolved around international affairs, and climate is one of those big global issues that has influenced me over the years. Climate now pervades discussions, from local to global; indeed, it is increasingly at the heart of many of our decisions, whether they are in the public or private sector. To underscore this fact, climatologists now sit alongside other specialists when major public policies are being discussed.

As this Digest goes to print, the Fifth Conference of the Parties (COP-5) to the Framework Convention on Climate Change (FCCC) is wrapping up its meeting in Bonn, Germany. This conference is one in a series of steps to prepare FCCC implementation for the future entry into force of the Kyoto Protocol. There are 5,000 people present, more than two thirds from non-governmental organizations. In short, it is the way the world's governments, with the private sector and NGOs, are preparing to address the issue of climate change, change that has profound implications for us all.

The Canadian Institute for Climate Studies is making its own contribution to this global concern. Its work is widely respected both in industry and in government. Its staff and affiliates are first rate in their fields, have broken new ground in the past and I anticipate they will so so in the future as well. One of the positive signs that I see occurring is that Climatology, thought previously as a science looking at past evidence, is now helping us look forward. The Board has directed that the Institute now take a forward looking approach, one which provides industry with a window on climate - assisting Canadians to prepare for the future.

This is an exciting time, and I invite you to join us as we move forward. •

Dr. Gordon Smith

From the Executive Director

I would like to take a moment to recognize one of our main supporters and clients – the Atmospheric Environment Service of Environment Canada. As many of you know, CICS manages the Climate Research Network. This network of basic and applied climate researchers is wholly funded by the federal government and it delivers world class research. We are proud to have this unique window on climate research in Canada and I encourage you to read the reports from its Principal Investigators on their most recent findings. These are located on CICS' website at http://www.cics.uvic.ca/climate/crn/index.htm.

As you will discover in this issue of The Climate Network, climate change has many different faces: – practical concerns, basic research and emerging issues. To explore these faces we have selected long term trends in the climate over Canada, the carbon cycle and sudden climate change. Each topic in itself is a separate study but with strong interdependences to the others. Understanding climate and its impact on business is more than theoretical interest; it will impact on virtually all business to some degree in the coming decades, if it has not already.

Climate change is more than climate warming. Its aspects includes how the rainfall pattern will change globally and locally, how the snowfall will change as the freezing level rises, changes in cloudiness at popular resorts, more frequent storms affecting transportation and more or less wind. In fact any business whose clients think about weather – ski resorts, nurseries, construction and transportation can benefit by learning how climate change may influence their viability in the years to come. CICS is ready to assist you in this area and we welcome enquiries.

Change comes to all organizations and CICS is no different. At a recent Board meeting it was decided to place more emphasis on assisting business through services in education, advice and research. CICS will review its current suite of products and methods of delivering the products – perhaps a shift toward greater use of Internet delivery, which many of CICS members and clients currently use.

At the same meeting Dr. Gordon Smith was elected as Chairman of the Board. It gives me great pleasure to welcome Gordon. He comes with extensive background in policy at the national and international levels, he has held several Deputy Minister Federal Government appointments, and is also the Chair of several Centres whose work is related to that of CICS. We look forward to his perspectives on climate issues. •

Fred Herfst

New Members

Companies

- Memorial University of Newfoundland, St.John's Nfld
- Royal Roads University, Victoria, BC
- Stittco Energy Ltd., Calgary
- Renaissance Energy Ltd., Calgary
- Midwest Foods, Carberry
- Quadra Energy Trading Ltd., Calgary
- CGU Group Canada Ltd., Scarborough
- Resource Integration Systems Ltd., Toronto
- AltaGas Utilities Inc., Leduc, AB
- NRCAN– Canadian Forest Service, Ottawa
- Environment Canada, Regina
- AXYS Technologies, Sidney, BC

Individuals

- Dave Wilcox
- Ray Keller
- Mr. Brian Hanlon
- Shauna Sigurdson
- William Shaw
- Catherine McMullen
- Robin Owens

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Trends in Canadian Precipitation Intensity

When people talk about climate change they often consider only changes in the average climate. Will it be hotter this summer? Will it be wetter? However, climate can also change in other ways. It may get more or less extreme even while the seasonal or annual average remains constant. For instance, rather than receiving, say, ten days of 10 mm rainfall in June, the same amount of rain may fall in just two days of 50 mm. Obviously this is a simplified and exaggerated example but even much smaller changes in the frequency and intensity of extreme events can be very important.

Introduction

Changes in the frequency and intensity of climate extremes could have important social, economic, political and environmental consequences. Consequently, we must research changes, past, present and future in these extremes. What were the seasonal and regional characteristics of past changes in the frequency and intensity of extreme events? What were the effects of these past changes? Were such changes related to changes in the average large-scale climate? Are extremes becoming more or less frequent and intense today? Are they predicted to become more or less frequent under enhanced greenhouse warming? Can we already see such changes?

Weather and climate involve the redistribution of water in the climate system (i.e. the atmosphere, the ocean, the land surface and sea ice). For instance, the redistribution of water plays central roles in the development of clouds, rain, snow and wind and in humidity and the moderation of temperature. In the case of climate extremes, water is just as important. Lengthy precipitation deficits lead to decreased production from the agricultural, forestry and power (hydroelectric) industries, municipal water supply shortage, costly forest fire suppression and wind erosion. On the other hand, prolonged periods of heavy precipitation lead to flooding, infrastructure damage, water erosion, costly snow removal and adverse driving conditions.

As the world's population grows, areas more susceptible to natural disasters such as coastlines and flood plains are becoming more intensely populated. We are also becoming much more dependent upon various networks of increasing size. Power, communications, transport and travel networks for instance, now cover vast areas, ranging from continents to the entire globe. These networks depend upon the functioning of various nodes and so are susceptible to natural disasters. For these reasons human society in general is becoming more and more susceptible to climate extremes even if distant from the event itself.

Clearly we must try to predict future changes in climate extremes in order to be prepared for potential natural disasters. Under global warming, physical arguments suggest that extremes in precipitation will indeed become more frequent and intense under enhanced greenhouse warming. Thus warmer temperatures should lead to more evaporation, more vigorous atmospheric convection and more violent storms, resulting in more extreme precipitation. Complex simulations by global climate models elaborate on these predictions, showing that such changes could be regional and seasonal in nature, with larger changes occurring in some places and seasons and smaller changes and even decreases in extremes, occurring in others. The overall increase in extreme precipitation is predicted to be strongest in high and middle latitudes where the largest warming should occur. Thus along with warmer temperatures, Canada can expect more extreme precipitation under enhanced greenhouse warming.

Precipitation intensity

Considering this importance, several studies have recently examined changes in the frequency of extreme precipitation in the past century. These studies have only examined the precipitation records of a few countries so the results cannot be extrapolated to the entire globe. In the United States for instance, extremes have become significantly more frequent over the past century, concurrent with an overall increase in the total rain and snowfall. On the other hand, they have become less frequent in Australia. In both countries, year-to-year changes in the frequency of precipitation extremes are related to the occurrence of El Nino and La Nina events.

It would be interesting and important to find out if similar changes and relationships exist over Canada. Considering this, I recently examined Canadian data for changes in extreme precipitation over the last century. This investigation was collaborative with Dr. A.J. Weaver (University of Victoria) and Dr. F.W. Zwiers (Canadian Centre for Climate Modelling and Analysis) (see Stone, D.A; Weaver, A.W. and Zwiers, F.W. 1999. Trends in Canadian Precipitation Intensity. J. Climate, submitted). For this project we used daily station records for 69 stations spanning the country. Data were obtained from the Climate Research Branch of the Atmospheric Environment Service. While measurements have been taken in southern regions of the country since the beginning of the century, measurements for the north began only about fifty years ago. Thus, country-wide analyses are limited to the 1950-1995 period.

When examining data, one must group samples together to help interpret the results. However Canada is a huge country and a simple national analysis does not illuminate the regional climate structures. For instance, while extremes could be increasing in one region, they could be decreasing in another. Nationally this would add up to little overall change when in fact, large changes were taking place. In the case of precipitation, Canada can be divided into five large regions based on similarities between stations' precipitation statistics. They are: the Southeast (the Atlantic provinces, Southeastern Quebec and Southern Ontario); the Northeast

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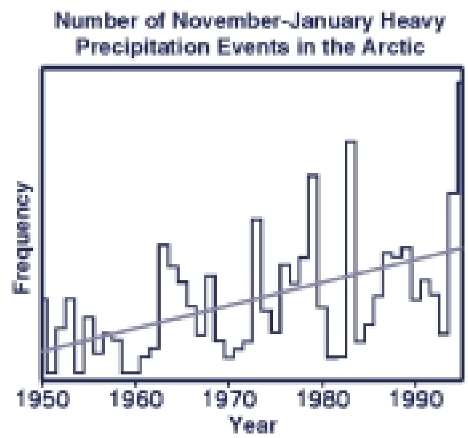
(Northern and Western Quebec, Northern Ontario and Baffin Island); the Arctic (the Arctic Islands except for Baffin Island); the Southwest (the Prairies provinces and British Columbia); and the Northwest (Yukon and most of the mainland Northwest Territories).

One of the greatest difficulties in analysing extremes is in the definition itself. What is an "extreme event?" One favoured method is to count every "event" (usually a day) above a fixed threshold (e.g. 50 mm) as an extreme. Another method uses a more flexible station-dependent threshold, corresponding to, say, the top 10% of events at each station. Both methods have advantages and disadvantages. An alternative is to use a hybrid definition taking advantage of the best elements of both methods. This method can also be extended to define other classes of intensity. Thus we can divide the daily events at each station into three classes: light,intermediate and heavy. This allows us to compare changes in the frequency of heavy events with those of the more common lighter events. Using these definitions we can examine the changes in the frequency of events in each of the three intensity classes for each of the five regions.

Trends in precipitation intensity

The most obvious feature of Canadian precipitation data is a significant trend towards greater precipitation. This trend was present in the Southeast and Southwest over the entire century, amounting to 1.5-2.0% of the 1960-1990 average per decade. This trend occurred in all three classes of intensity and during most seasons. Over the past fifty years this trend has tended to occur only in intermediate and heavy events in this area, during the summer and autumn.

Northern regions show an even larger increase in total precipitation over this time. For instance accumulations in the Arctic have increased at a rate of 7% per decade. As in the south, these increases are due to an overall increase in the frequency of heavier events. In fact, the frequency of light events has remained constant over this time. In the three northern regions the increases have occurred during the autumn, winter and spring, with no significant change occurring during the summer. In the Arctic, for instance,



heavy events during November through May have become more frequent at a rate of 20% per decade, amounting to almost a 100% increase since 1950. (Figure 1)

Relationships with large scale climate

While the increasing trend, both in total precipitation and in precipitation intensity, is the most obvious feature of the Canadian precipitation record, other important changes have occurred in some regions. For instance, the three driest years of the twentieth century in the Southwest of Canada were 1928, 1929 and 1930, corresponding to the "Dust Bowl" years; however, only the autumns and winters were dry at this time; the springs and summers received average amounts of precipitation. This drought was also related to changes in precipitation intensity. While these years received very few heavy and intermediate events during the autumn and winter, light events did not become less frequent.

Later, the Southwest received less precipitation than normal in most years from 1976 through 1988. Similar to the 1928-1930 dry period, this resulted from less precipitation in autumn and winter, extending somewhat into spring; however, in this case intensity was not affected; events in all three classes of intensity were less frequent at this time.

An obvious question and one of great importance to the agricultural industry in this region, is whether these dry periods and changes in intensity are related to changes in larger scale climate phenomena. Many of the driest and wettest years in this region have occurred during El Nino and La Nina years, respectively. During these years surface temperatures in the eastern Tropical Pacific Ocean are much warmer (El Nino) or colder (La Nina) than normal. Such large changes in temperature over such a large area of Earth's surface force changes in global wind patterns, with effects detected around the planet. Over North America, the change in wind patterns that generally occurs during El Nino and La Nina years is known as the Pacific/North America teleconnection pattern (usually abbreviated to "the PNA"). During "positive" PNA (i.e. El Nino) winters, the North Pacific Jet Stream generally moves southward, thus bringing the wet weather normally received along the British Columbia coast (and to a lesser extent the Prairies) to the California coast. During "negative" PNA (i.e. La Nina) winters, on the other hand, the Jet Stream becomes stronger but does not move, bringing more wet weather to the Southwest region.

While changes in the PNA affect the total precipitation, they do not affect the intensity in Southwestern Canada (Figures 2 and 3). Events of all three classes of intensity occur less frequently during positive PNA winters and more frequently during negative PNA winters. However, the PNA and thus El Nino and La Nina, do not affect only the Southwest: Ontario and Southern Quebec are also affected. Like the Southwest, this area receives less precipitation during positive PNA winters and more during negative PNA winters; unlike the Southwest, intensity is also affected in this area. (Figures 2 and 3)

During positive PNA winters this area receives fewer heavy events than normal, but just as many light events as usual. During negative PNA winters it receives more heavy events, while light events remain normal. Thus the PNA affects the intensity of precipitation in Ontario and Southern Quebec. In fact, this

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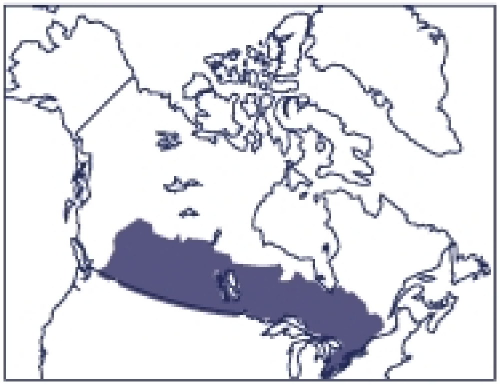
Trends in Canadian Precipitation...

Areas where the PNA Affects Heavy Precipitation



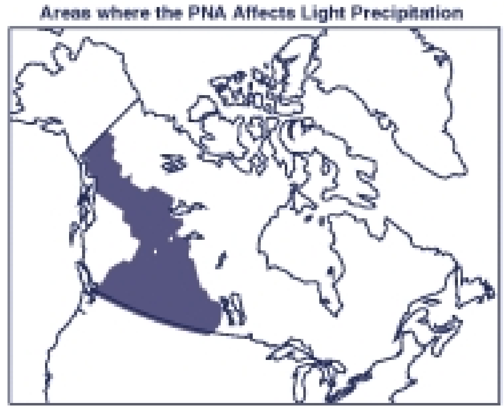
response in extreme precipitation is more robust than the change in total precipitation occurring during these years.

These results are important for use in seasonal prediction. The PNA is the main mechanism through which El Nino and La Nina events affect Canadian climate. These events are predictable several months in advance, a useful length of time for seasonal climate predictions. By predicting these events in advance, the strength of the PNA and thus the total precipitation and its intensity, can be predicted for the winter. Since large, populated and agriculturally-important regions of the country are affected, such predictions could be useful.

Conclusion

At the beginning of this article we asked some important questions about extreme precipitation in Canada. By examining the daily precipitation record we found that changes in the frequency of extremes were related to drought periods, demonstrating that indeed changes in precipitation intensity do affect Canadian society. Moreover, some of these changes were related to changes in large scale climate, for instance the atmospheric circulation anomaly known as the Pacific/North America tele-connection pattern. The PNA pattern is also associated with changes in the intensity of precipitation in Ontario and Southern Quebec. We also found that extreme heavy precipitation events are more frequent now than in the past. This is especially the case in northern regions where the largest increase has occurred, consistent with enhanced greenhouse warming projections.

Areas where the PNA Affects Light Precipitation



Dáithí Stone has just completed his M.Sc. Thesis on observed changes in Canadian extreme precipitation. He is presently starting Ph.D. Studies on climate variability at the University of Victoria's Climate Modelling Group. •

Carbon — the Heart of Climate Change

by Trevor Murdock

Carbon forms the basis of all life on the planet. It is found in the oceans, in living biomass and in the lithosphere (e.g. coal). Just how carbon moves to and from these three main storage areas – is the key to understanding what we call the 'Carbon Cycle.' Although our present knowledge of this cycle is incomplete, it can help our understanding of some important questions:

How severe will impacts of climate change be? How much do we need to reduce carbon emissions in order to reduce impacts of climate change? If the climate system is perturbed [given a push], will the current climate re-establish itself or perhaps shift to a different climatic equilibrium? If so, after how long?

Other than reducing fossil fuel emissions, are there other ways of reducing carbon dioxide levels in the atmosphere? How does the current situation compare to the past climate record?

Sources and Sinks

The basic components of the carbon cycle are depicted in the accompanying figure and comprise: -'sinks'- processes through which carbon dioxide is removed as a gas from the atmosphere and stored, and 'sources' – processes in which carbon dioxide gas is released into the atmosphere from one of the sinks.

The major sinks in approximate order of largest to smallest are marine sediment and rock, ocean, fossil fuel deposits, soil, forests (and all plants) and lastly – the atmosphere, the smallest but most significant sink. The size of some of these major sinks of carbon is currently the subject of much debate as the uncertainties in estimating their quantities are still fairly large.

Of course the earth-atmosphere-ocean system contains a fixed amount of carbon and it is the relative amount in each part of the system at any time that is crucial. Our primary concern is the amount that remains in the atmosphere as carbon dioxide.

Transferring Carbon between Sinks

The mechanism for carbon dioxide 'uptake' by the ocean is diffusion – the atmospheric carbon dioxide essentially dissolves into the ocean. While some carbon is stored in the ocean itself, it is also precipitated out of the ocean (sinks to the bottom) as calcium carbonate deposits which eventually turn into sediment and rock. This in turn allows more carbon to

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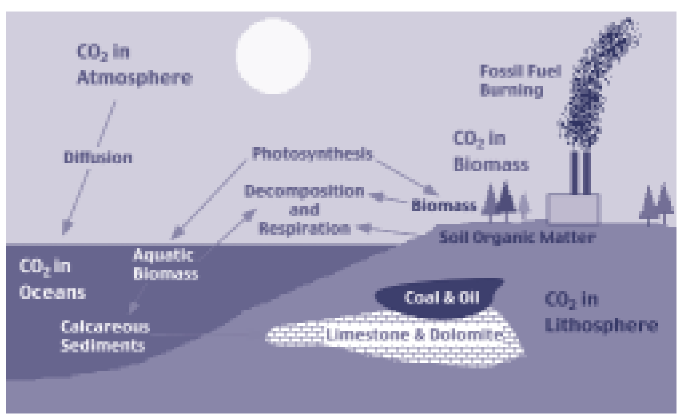
diffuse into the ocean. Naturally, this is an oversimplification of a more complicated process that is also influenced by several other factors such as the temperature of the water surface, the rate and depth of ocean mixing and surface plankton.

Carbon dioxide uptake by forests and other plants takes place through photosynthesis which locks carbon into living biomass as well as into the soil. Locking carbon dioxide into biomass is actually temporary, as eventually it becomes a source to the atmosphere through decomposition of organic matter. Removal of biomass for example through cutting of forests in itself does not result in an immediate decrease of biomass. Wood is used in structures and carbon remains stored. Only the by-products of forestry left to decompose become immediate sources of carbon for the atmosphere. As long as the amount of carbon that is released to the atmosphere equals that which is sequestered by living biomass, the total carbon capacity remains constant. When forests are removed the capacity diminishes. When land is reforested the capacity increases.

Respiration in the above diagram represents the symbiotic relationship of animals to plants where animals breathe in the oxygen produced by photosynthesis and breathe out carbon dioxide, which plants then use in photosynthesis and produce oxygen again. This is a relatively small portion of the carbon cycle so that changes in this type of carbon dioxide do not affect the overall picture significantly. Finally, since the beginning of the industrial revolution, humans have added a new source of carbon dioxide to the atmosphere – through the burning of fossil fuels. The result has been an increase in atmospheric carbon dioxide levels by about 30%. In the context of global warming, this is essentially an irreversible process because once depleted fossil fuels cannot be re-synthesized and stored as they once were.



Pidwirny, M. 1999 Fundamentals of Physical Geography. http://www.geog.ouc.bc.ca/physgeog/

Debates

Burning of fossil fuels is not the only human activity or 'anthropogenic' source of carbon dioxide. Changes in land-use also have been a major contributor. Cutting of forests and tilling of land have resulted in a net increase of carbon in the atmosphere since the 1700's. In recent decades, growth of new forest has in fact provided increased storage– a temporary sink– for carbon. Recent findings published in the New Scientist however, suggest that relying on new forest for carbon uptake may be dangerous as estimates of the capability of forests to act as sinks are grossly overestimated simply because plants do not respond beyond a certain level of atmospheric carbon dioxide and some scientists believe that point is near. In the long term, forests can only retain carbon if the land is left to forestry in perpetuity. Even then, suggestions are now being made that as the global temperature rises, plant matter will decay and release carbon dioxide into the air, ultimately making forests a net contributor of carbon dioxide. The wisdom of using forests as a permanent sink is thus coming into question.

The debate over the capacity of carbon sinks is not restricted to forests. Carbon sequestration – the artificial and natural trapping of carbon dioxide in a sink to remove it from the atmosphere – is an intense area of ongoing research that has recently received some major boosts in funding in the US. Potentially promising areas of carbon sequestration research include: - conversion of agricultural practices to non-tilling or conservation tillage; binding of carbon dioxide to minerals; pumping liquid carbon dioxide deep into the ocean; and, artificial stimulation of oceanic uptake of carbon. None of these methods of storing carbon however, would be as effective as keeping carbon stored in its fossil form. This means civilization needs to convert to sustainable energy sources such as solar radiation and wind. There are many hurdles to overcome to achieve effective carbon sequestration – including ensuring potential carbon sinks are not temporary nor damaging to the environment.

Some of the most daunting unanswered carbon cycle questions surround potential 'positive feedback' mechanisms. An example of a positive feedback mechanism is found in Arctic permafrost. Initial global warming melts snow and ice, changing the surface albedo [reflective qualities of the earth's surface]. Land areas no longer covered in white snow or ice absorb more of the sun's radiation, the land warms and the permafrost melts, methane and carbon dioxide are released from peat which enhances the greenhouse effect and leads to more global warming. Melted permafrost is believed to be a potentially major source of greenhouse gases. Recent warming in the Arctic regions has focussed research on this feedback mechanism and much remains to be learned.

The Carbon Cycle in the Past

What is known about fluctuations in atmospheric carbon dioxide levels in the past? How do the current levels compare to historical peaks? Research findings in this area recently received a major boost with the completion of the analysis of the Vostok ice core record. This Antarctic record shows the fluctuations in atmospheric carbon dioxide levels (as well as methane) over the last 420,000 years. Four peaks in carbon dioxide levels have

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been identified during this record, all of which were smaller in magnitude than the current carbon dioxide concentration in the atmosphere. When this record of atmospheric carbon dioxide is placed in juxtaposition to Earth's temperature, a picture emerges.

It appears that carbon dioxide level changes in the past were accompanied by similar rises and falls in temperature. There is also some linkage to solar radiation fluctuations, but that relationship is not nearly as strong as between carbon dioxide and air temperature.

According to the scientists analysing the Vostok cores, not only are carbon dioxide levels currently higher than at any point in the last 420,000 years but also these levels continue to increase at a rate greater than observed in the past. It is disturbing to note that after each peak the global temperatures dropped two degrees, sometimes rapidly, sometimes gradually. Temperatures then fell slowly over several millennium into glacial conditions. We are left to wonder if human activity could accelerate the arrival of the peak atmospheric loading of carbon dioxide and thus usher in the next cycle of glaciation prematurely?

Clearly there are important issues to be addressed, not only in the manner in which we produce energy but also in understanding the carbon cycle, anthropogenic influence on the cycle, carbon sequestration and potential for positive feedback mechanisms. There continues to be a need for further research that will lead to a deeper understanding of climate and to improvements of models of climate change. •

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Rapid Climate Transitions

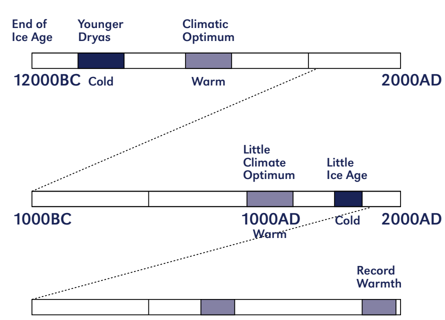
for instance, the freezing of the Nile and Black Sea; the Little Climatic Optimum around 1,000 AD made possible the exploration and settlement of the east coast of North America; the retreat of glaciers in mid-high latitudes of North America is part of climate change that has been ongoing for two hundred years; and lower sea levels as much as 2 to 3 metres, have been linked to colder periods in the earth's past. All these impacts give reason to consider the likelihood of climate change and especially rapid climate change.

There is mounting evidence that climate can and does change in a stepwise manner taking a relatively short time to shift from one climate state to another, as appears to have occurred during the Eemian – a similar warm climatic period that occurred about 130,000 years ago.

And even during the Eemian period, there is evidence of sudden punctuations in this interglacial warm period affecting geographic areas on a continental scale and lasting several hundreds of years. In the context of today's global warming, based on similar periods in the past, there is the possibility that the anthropogenic-induced warming might be terminated with rapid cooling to a colder state of affairs.

If rapid climate change is possible, it could have a dramatic impact on civilization – many parts of our physical infrastructure and food supply would have at best difficulty in coping with change-ports, engineering works, buildings, agriculture and forestry to name a few. There is concern in some circles that the current anthropogenic influence on climate might be sufficient to push the climate system 'over the top' and initiate a sudden global climate change. What then causes these dramatic and rapid changes?

There are a number of ideas about the source of rapid climate change, one of the most prominent of which relates to the 'Oceanic Conveyor Belt' (OCB). The OCB is a major, but very slow ocean



circulation in which warmer water brought into the North Atlantic by the Gulf Stream cools and mixes with saltier water from the Mediterranean sinks to the ocean floor due to its higher density then moves southward to the Antarctic. The circulation is completed when this water travels to the Indian and Pacific Ocean, rises to a shallow current then returns to the South and North Atlantic Oceans. Despite the slow speed of movement of water, it transports a large amount of heat into the North Atlantic, heat which prevents the northern-most parts from freezing.

When a trigger event intervenes in this oceanic circulation, such as unusually large quantities of fresh water flooding into the North Atlantic from glacial melt, ice melt or an extreme precipitation event, ice coverage is thought to expand across those regions where water normally sinks to the ocean floor. This layer of less dense water slows or stops the sinking, reducing or stopping the Gulf Stream and the OCB. The effect of this broad coverage of ice would cause the whole western Europe to cool, bringing on a regional 'cold age.' Such a change is thought possible to occur in a very short period of time, perhaps years, and there is evidence to suggest this has occurred in the past.

Other hypotheses about mechanisms which might trigger a rapid climate transition are less compelling. Nevertheless they might contribute by bringing together circumstances under which rapid climate change could occur with a slight 'push' akin to coming to the limits of a buffering process or stretching something physical to the breaking-point.

One of these potentially contributing processes is the build-up of carbon diox-

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ide and methane acting as greenhouse gases. It is unlikely that they would be the sole cause of rapid climate change as they involve transfer processes between oceanic and terrestrial storage mechanisms which typically take thousands of years. However by perturbing the natural variability with additional greenhouse gases, the concern is that we may reach a break-point sooner rather than later.

Another possible mechanism is a change in the reflectivity of the earth's surface due to alterations in coverage and character of sea and land ice, snow and vegetation. Ice and snow reflect solar energy whereas vegetation generally acts to absorb it. Vegetation also serves to reduce dust. The gist of this hypothesis involves gradual change in the radiative balance of the earth, which over a long period of time brings the climate system to a 'break point'. Then other mechanisms could trigger, for example, a major temperature change. There is evidence to suggest this mechanism was involved in the ending of the Younger Dryas period in a remarkably short period of time which appears to have occurred with several warming steps of 5 to 15 years.

Dust and atmospheric particulates are a likely source of rapid climate change. During colder periods in the climate history, dust appears more frequently in ice core samples. Dust reflects sunlight, cooling the earth and producing a more arid climate which in turn provides more sources of dust. Evidence of this effect is readily seen from the impact of major volcanoes which inject huge volumes of dust into the earth's atmosphere, cooling the earth's climate for several years thereafter. A change in atmospheric circulation from other causes could bring back greater precipitation, reducing dust and increasing vegetation and radiation absorption, warming the climate, bringing the cycle to its origin.

A further possibility on a long time scale relates to changes in solar energy due to changes in the orbit of the earth. These were discussed in the Fall 1999 edition of The Climate Network. Axis orientation, the elliptical shape of the orbit, and timing of seasons all factor into how solar radiation varies. The concept advanced here is that while sunlight intensity varies over thousands of years, it may bring the climate system to a 'break point' at which time other factors could cause a sudden transition in the climate. The historical records do not support solar radiation as a mechanism for rapid climate change as those instances where such change has occurred do not correlate with the solar cycles.

There are relatively few cases where rapid changes have been documented, and with reason. Such detail is relatively difficult to amass when we consider that the time resolution in historical proxy data is of the order of decades while the historical record stretches over millions of years!

Identifying rapid climate change events is one thing; determining the cause is another. From the discussion above, there is clearly an incomplete understanding of the physical processes involved. At this juncture, the processes could be relatively straight forward, involve trigger or feedback mechanisms or simply implicate a number of (natural variability) processes which come together at a moment of time, not unlike wave trains on the sea which cause a rogue wave to appear then vanish. Rapid climate change is a distinct possibility and merits further consideration.

This is based on an article in press in Physical Geography as posted at www.esd.ornl.gov/projects/qen/transit.html as well as other sources. •

Upcoming events

AGU Fall Meeting
3–17 December, 1999,
San Francisco CA, USA,
meetinginfo@agu.org

11th Symposium on Global Change Studies
9–14 January 2000,
Long Beach California, USA

80th Annual Meeting of the American Meteorological Society
9–14 January, 2000
rdobson@ametsoc.org

World Clean Energy Conference
24-28 January, 2000, Geneva
icecag@zik.ch

AAAS Annual Meeting and Science Innovation Exposition
17–22 February, 2000,
Washington DC, USA
confinfo@aaas.org

Xth World Water Congress
11–17 March, 2000,
Melbourne, Australia
worldwater@icms.com.au

11th Global Warming International Conference and Expo
25–28 April, 2000, Boston, USA
syshen@megsinet.net

12th AMS Conference on Applied Climatology
8–11 May, 2000, Asheville NC, USA
atd2@cornell.edu

34th Annual CMOS Congress
29 May to 2 June, 2000,
University of Victoria, BC
George.Boer@ec.gc.ca

Climate Change Communication
June 22–24, 2000, Kitchner-Waterloo
http://geont.uwaterloo.ca/c3confer/

Watershed 2000
July 9–12, 2000, Vancouver, B.C.
pattersonj@pac.dfo-mpo.gc.ca

Meteorology at the Millenium
10–14 July, 2000, Cambridge, UK
execsec@royal-met-soc.org.uk

The Extremes of the Extremes: International Symposium on Extraordinary Floods
17–19 July, 2000, Reykjav¡k, Iceland
asn@os.is

3rd European Conference on Applied Climatology (ECAC2000)
16–20 October, 2000, Pisa, Italy
falchi@sunserver.iata.fi.cnr.it