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Feedbacks Could Amplify Global Warming Beyond Current Predictions

*By Benjamiin DeAngelo, EPA's Stratospheric Protection Division **

Ben DeAngelo

Current predictions of global warming and associated climatic changes resulting from human activities are based on sophisticated climate models, which do not, however, in every case include important interactions between the climate and marine and terrestrial ecosystems. But scientists recognize that changes in these interactions could produce "feedbacks" which could either amplify or dampen expected rates of global warming and climatic change.

Feedbacks can be either positive or negative (i.e., dampening). As rising atmospheric concentrations of greenhouse gases, including carbon dioxide (CO_2) and methane (CH_4), lead to global warming, both the increase in greenhouse gases and the warming

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INSIDE

Guest Column by Dr. Gordon MacDonald of IIASA on how atmosphere and oceans "remember" patterns.

Editor's Note: Lurking in the background in discussions of climate change is the possibility of sudden, uncontrollable shifts, feedbacks from large deviations in ocean currents, for instance, which may bring unexpected impacts. In Volume 10, Number 2, we devoted an issue to extreme weather events: huge floods, intense rainfall, prolonged droughts which could occur in the near future. In this issue we have asked a group of experts to describe climatic "surprises," events such as an abrupt rise in sea level that may threaten us in the next 50 or 100 years or later (although some events, as Dr. Hughes points out, could arrive much sooner). David Walton of the British Antarctic Survey has suggested that climate negotiators think ahead more than the next few years and instead consider the longer term and how we can maintain a system which will allow all of us to persist.

Climate Surprises Could Spring from Changes in River Flow, Ice Sheets and Sea Ice

Dr. Terry Hughes *of the University of Maine at Orono in a telephone interview delved into many sources of unforeseen climate events. We are saving his interesting remarks on how icebergs from West Antarctica may affect El Ninos for a later issue of Climate Alert.*

River flow

The Mackenzie River in Canada and the many rivers in Siberia: the Ob, Yenisey, Lena, and Indigirka, drain enormous areas. While they are frozen in winter, in summer they carry a very heavy discharge. Under greenhouse warming, the rapid runoff would be extended a few weeks at each end of the summer season, two to three months in all, and the pulse-like discharges would probably be much heavier. A large influx of fresh water would have a big effect on sea ice which is delicately balanced. Warmer winters bringing more precipitation could upset that balance, increasing the thickness by a few centimeters per year. There would be a change in the interglacial balance, both in thickness and to a much larger extent in area of sea ice. There is a question of how the mass balance would shift. If

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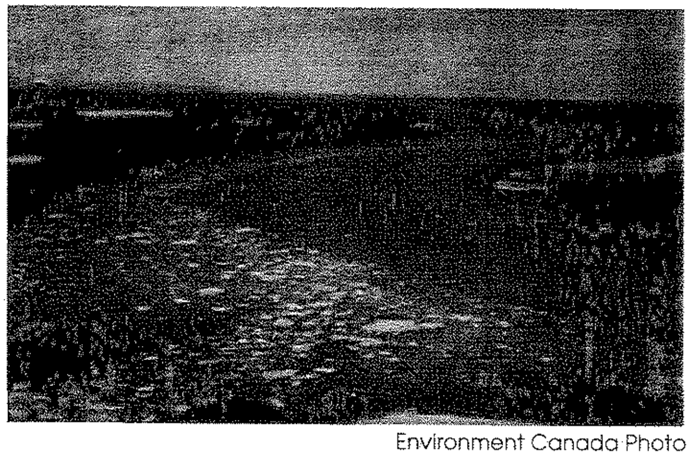

Environment Canada Photo

The Mackenzie River at very high flow.

GUEST COLUMN

Ocean/Atmosphere Memory Makes Extreme Events More Likely

By Dr. Gordon J. MacDonald, Director, International Institute for Applied Systems Analysis, Laxenburg, Austria

Gordon J. MacDonald

Discussions of global change often emphasize changes in the mean global temperature, where the average is taken over the globe and over the year. Depending on the particular climate model used, the expected changes are on the order of 1 to 4 degrees Celsius for a doubling of the concentrations of carbon dioxide. As has often been pointed out, changes of this magnitude can be achieved by moving a relatively small distance north or south, or even moving 1000 m down a mountainside.

Statistics such as mean temperature, therefore, do not capture the true implications of climate change. Instead, economic costs and social disruption arise from extreme atmospheric events, such as hurricanes, typhoons, floods, droughts, windstorms, or prolonged periods of cold. The most significant issue in future climate change is whether these extreme events will become more frequent and/or more intense. In statistical terms, the question is how the probability of extreme events that are characterized by the thickness of the tails of the distribution will change with alteration of climate. Most current climate models do not capture the climatic extremes for a variety of reasons, including that the spatial resolution of these models is inadequate to represent many extreme events.

Spatial Correlation

Means and standard deviations can be exceedingly useful statistics for describing independent events, such as coin-tosses. But weather events are not independent, either in time or in space. For example, a typical high-pressure system has a spatial scale on the order of 1000 km, and, in the Northern Hemisphere summer, an air mass circulating clockwise about a high-pressure center generally remains over a given geographical area for a few days. During that interval, weather at various points in the region is correlated both spatially and temporally. Thus, a prediction that the next day's weather at a particular site will be similar to today's stands a good chance of being correct. Stated another way, the spatial correlation implies that the atmosphere has a memory. What happens today depends on what happened in previous days.

Role of Memory

Independent events commonly exhibit the normal or bell-shaped statistical distribution. In such cases, the tails of the distribution are very thin and the probability of extreme events is low. By contrast, when there is memory in the system, as is the case in the atmosphere, the tails of the distribution become thicker and the probability of extreme events rises as correlated events combine to yield larger deviation from the mean.

In considering climate, the ocean interactions with the atmosphere are critical. The large thermal capacity of the ocean makes it able to influence the thermal character of the overlying atmosphere. However, unlike the atmosphere, with correlation times on the order of days, motions within the ocean have time scales of years and decades, perhaps even longer. Thus, atmospheric events can also show correlations over periods of years and decades. The ENSO (El Nino, Southern Oscillation) phenomenon clearly illustrates the role of the oceans, as every few years a warm pool of water builds up off the west coast of South America, bringing torrential rains to desert regions and influencing climate over much of North America. A North Atlantic oscillation demonstrates a somewhat analogous phenomenon in the Atlantic circulation. Satellite observations show that anomalies in the Atlantic sea surface temperature migrate northward with a time scale of a decade. The northward travelling sea surface temperature anomalies give the ocean a memory of past atmospheric conditions.

More Extremes Likely

These correlated events lead to thicker tail distribution and a greater frequency of extreme events than would be expected if weather were made up of a sequence of independent events. For example, the pool of warm water found off the coast of Florida — probably associated with 1992's Hurricane Andrew or possibly with Hurricane Hugo in 1989 —

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120 Maryland Avenue, NE
Washington, D.C. 20002
Phone: (202) 547-0104
FAX: (202) 547-0111
E-Mail: ncwilson@climate.org
Web: http://www.climate.org

may in part be responsible for the flooding of Central Europe during the summer of 1997.

In fact, flooding provides a good example of extremes, as illustrated by El Nino events. Because evaporation depends exponentially on temperature, warm surface waters pump into the atmosphere at a greater rate than cooler waters. As long as the pool of warm water is exposed to the atmosphere, the atmosphere will carry the water over continental areas, leading to increased rainfall and increased probability of flooding.

The long-term memory of oceans implies that heavy rainfalls may persist over a given region for periods of years. Therefore, accumulated precipitation in river basins can give rise to disastrous floods that carry heavy costs. Flooding in Central Europe in the summer of 1997 was greater than any recorded in the last 200 years. To illustrate the impact of this catastrophe, the cost to Poland of the Oder floods of 1997 exceeded US$4 billion, or 4.4 percent of Poland's GDP.

Methane Hydrates

The vast quantity of methane contained in hydrates of methane stored in continental shelf sediments poses another potential long-term threat to climate stability. Exposing the sediments to warmer ocean currents, and the consequent diffusion downwards of the thermal load, could release this methane, which would then add significantly to the greenhouse gas burden of the atmosphere. Such releases cannot be confidently predicted because of the continuing uncertainty as to the long-term nature of ocean circulation.

The climate of the future is certain to bring surprises. The recently discovered rapid oscillations (100 years) in climate, shown in the ice core from Greenland, may have been associated with sharp shifts in ocean currents or with totally new processes not yet discovered.

Feedbacks

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can affect the structure and function of ecosystems. Such effects may accelerate or diminish the warming and precipitate change of a different magnitude from the initial disturbance.

Historical evidence suggests that feedback mechanisms may have played a significant role in past climatic fluctuations, such as the apparent cyclical nature of the Earth's ice ages. Data spanning the past 220,000 years indicate that variations in temperature and CO_2 concentrations were strongly correlated, with CO_2 changes lagging behind temperature changes. It is a fair assumption that past warming resulted in the release of greater amounts of CO_2, which in turn could have led to further warming — a positive feedback.

Other Positive Feedbacks

- Model simulations of past climatic changes reveal that other types of positive feedbacks may have been at work as well. Long-term changes in the Earth's orbit — the apparent source of historical climatic changes — were, according to the models, insufficient to account for the full magnitude of past temperature fluctuations. An additional key driving factor seems to have been the poleward shift of forests into high-latitude grasslands, reducing the reflectivity (albedo) of polar regions, increasing absorption of sunlight, and producing greater warming compared to what was initially induced by orbital changes alone.
- Like these past natural changes, human-induced global warming over the coming century is expected to cause a poleward shift of forests, decreasing the reflectivity of the Earth's surface, increasing absorption of sunlight, and enhancing rates of warming.
- Warming in the high-latitude regions may bring expanded release of methane from moist bogs or peatlands. Methane is the second most important anthropogenic greenhouse gas in terms of its warming effect. Likely changes in soil moisture from global climatic change will also affect rates of methane emissions, but in less certain ways.
- Warming and associated decreases in soil moisture may bring about a rise in the number of natural fires. The burning vegetation would pump even more CO_2 into the atmosphere.
- Elevated concentrations of CO_2 have been shown to stunt plant transpiration, the process by which plants release water to the atmosphere. Transpiration normally cools the surface; its reduction could bring even higher regional temperatures at the surface (although the global implications of this are not entirely clear).
- In soils, CO_2 "enrichment" could lead to changing ratios among important plant nutrients and in the process lead to decreased nitrogen availability. In this case, any stimulatory effect of increased CO_2 on plant growth could be constrained.
- As warming penetrates the ocean sediment layers, billions of tons of methane locked away in an icy mixture called gas hydrate (which is only stable under specific conditions of high pressure and low temperatures) could be released.
- Oceanic temperature rise from global warming could lower the solubility of CO_2 and turn some regional oceanic CO_2 "sinks" into sources.

Negative Feedback

Global climatic change is expected to aggravate rates of land degradation and desertification, stirring up windblown dust. Such particles cool the surface regionally, increasing atmospheric reflectivity

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Feedbacks

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(especially when the underlying surface is relatively dark).

Conclusions

These possible feedbacks are among the most important not adequately incorporated into current climate models. It appears their effect will be to amplify global warming, perhaps substantially, compared with current predictions. Based largely on historical evidence, for instance, it seems likely the reflectivity changes of poleward shifts of forests could greatly amplify a human-induced warming trend. The feedbacks from methane release also have a large potential to accelerate global warming.

Even some of the feedbacks included in Intergovernmental Panel on Climate Change (IPCC) projections may not be adequately represented. The negative feedback of the "fertilization effect" of CO_2 on plants— in which plant growth is stimulated and takes up more CO_2 — may be largely overestimated. A range of unpredicted ecological interactions and responses to climatic change are likely to curtail or even reverse the fertilization effect.

In short, many factors remain which could drive rates of global warming and climatic change beyond the current IPCC projections. The scientific community is working to improve our understanding and representation of such important processes. In the meantime, policy makers will have to consider the potential impact of these feedbacks when formulating strategies to minimize the risks of global warming.

* *The views of the author do not necessarily represent those of the EPA.* For more information on this subject, see "Terrestrial Ecosystem Feedbacks to Global Climate Change," by Lashof et al in Annual Review of Energy and the Environment, 22: 75-118, 1997

Heavy Rainfall Has Increased as Temperatures Have Risen Bringing Threat of More Damage in Future

By K. Hennessy and R. Suppiah, CSIRO Division of Atmospheric Research, Australia

Extreme rainfall events cause significant damage to agriculture, ecology and infrastructure, disruption to human activities, injury and loss of life. Any change in the probability of extreme rainfall would have important implications for engineering, insurance, town planning and many other activities. What follows is an assessment of past and future changes in extreme rainfall.

Observed changes

Changes in extreme rainfall have been reported for various regions. The US National Climatic Data Centre (NCDC) found an increasing trend in rainfall exceeding 50.8 mm/day since 1910 over the USA, but not in the former Soviet Union and China. Daily rainfall data from 1890 to 1980 in Japan show that more stations recorded their highest, second highest or third highest rainfall event in more recent decades. An increase in the rainfall threshold exceeded by the heaviest 10 percent of events (90th percentile) in Australia has been found since 1910. Unfortunately, these analyses represent a small fraction of the land surface and a very small part of the planet, so a global picture cannot be formed at this stage. The NCDC is addressing this issue in an extended analysis of extreme rainfall changes in the USA, Canada, Mexico, the former Soviet Union, China, Australia, Poland and Norway.

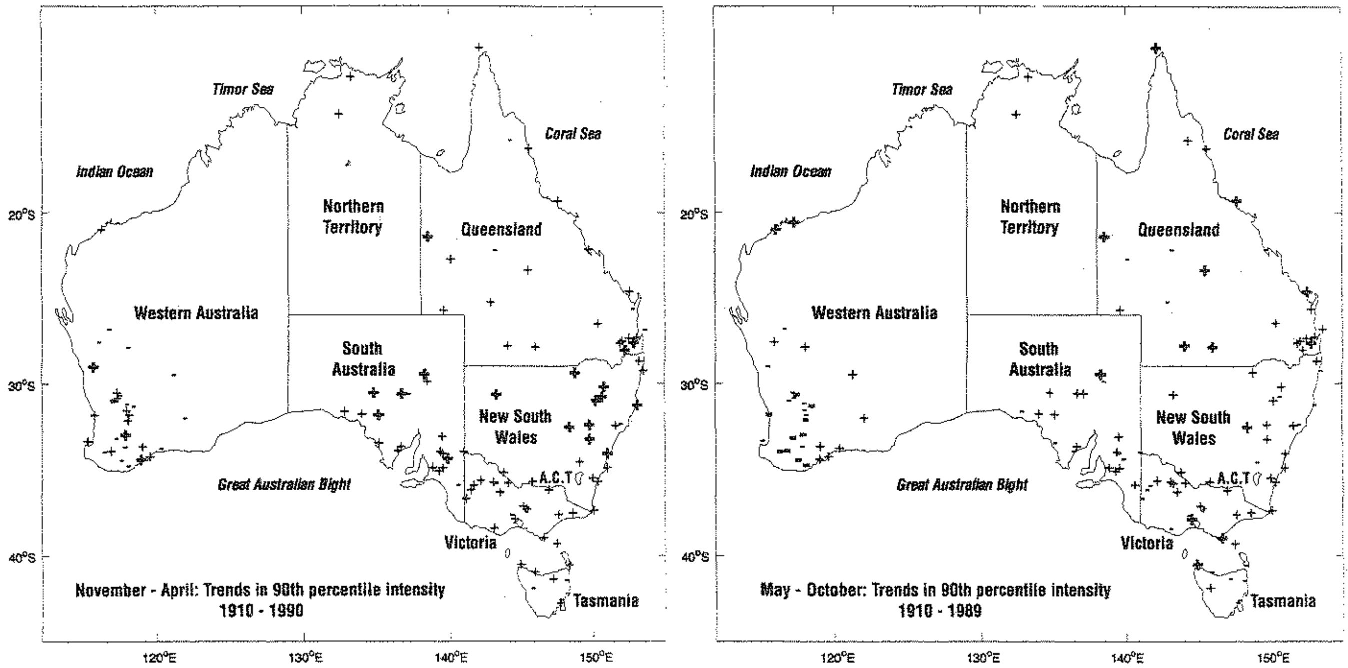
Increases in extreme rainfall in Japan, Australia and the USA have occurred during a period in which global mean temperatures have increased by 0.3 - 0.6 degrees C. At this stage, it is not clear what proportion of the observed warming and any associated increase in rainfall intensity is due to natural variability or to anthropogenic influences such as land-use change, biomass burning, ozone depletion and increased levels of greenhouse gases. Attribution of cause and effect is unlikely to be a simple task.

Future changes

Concentrations of greenhouse gases, particularly carbon dioxide (CO_2), are increasing in the atmosphere. This is expected to lead to global warming and climate change, some of which may already be evident. To determine the potential impact on extreme rainfall, global climate models (GCMs) are used. These models have a simplified representation of the atmosphere, oceans, land and icecaps. Variables like temperature, pressure and precipitation are computed at points 300-500 kilometers apart on a three-dimensional grid covering the planet. GCMs can simulate the continental scale behavior of the climate system but small-scale features like thunderstorms are not well resolved due to limited computer power. Climate change due to enhancement of the greenhouse effect is simulated by increasing the concentration of carbon dioxide (and sometimes other trace gases and aerosol) in GCMs.

Return Periods

Global and regional climate models from Australia, the United Kingdom, and Germany simulate a general increase in heavy rainfall (over 10 mm/day) frequency and intensity almost globally for a doubling of the present concentration of CO_2. Heavy rainfall return periods (the average interval between events of the same magnitude) were analysed in the UKMO, CSIRO4 and CSIRO9 GCMs. For a given rainfall intensity, the average return period becomes shorter by a factor of 2 - 5 (i.e. these events occur 2 - 5 times more often) over



Figures by Hennessy and Suppiah

Location of stations showing increasing (+) and decreasing (-) trends in the intensity of the 90th percentile daily rainfall from 1910 - 1990, during summer half-year (Nov - Apr) and winter (May - Oct). Larger symbols indicate trends statistically significant at 95% confidence level.

selected countries (Australia, India, Europe and the USA). Alternatively, for a given rainfall return period, the intensity of heavy rainfall increases by 10-25 percent for each country.

These results are based on simulations with GCMs having a grid resolution of 300-500 kilometers. Using such coarse resolution gives grid-box-average rainfall intensities which are much less than observed at a single location. More detailed and realistic estimates are to be expected from simulations with finer spatial resolution. Due to limited computer power, models with such fine detail can only be run over small regions. These regional climate models (RCMs) are driven at their boundaries by input from coarse resolution GCMs.

Regional Models

A number of RCMs have been used in enhanced greenhouse simulations, but few have been analysed for changes in heavy rainfall. The United Kingdom Meteorological Office (UKMO) RCM was run at about 50 kilometer resolution over Europe, driven by the UKMO GCM for 10 years of present and doubled CO_2 conditions. For the present climate, the number of heavy events (over 10 mm/day) in the RCM is generally at least double that in the GCM. For a doubling of CO_2, mean rainfall increases by 7-16 percent in the GCM and by 10-26 percent in the RCM. The frequency of heavy rainfall increases in the GCM by at least 50 percent and by 20-40 percent in the RCM. The reason for the smaller percentage increase in the RCM is the greater number of heavy events in the simulation of present climate. Actually, the change in the amount of precipitation associated with heavy events is larger in the RCM than in the GCM.

The CSIRO Division of Atmospheric Research RCM was run at 60 kilometer resolution over southeast Australia. It was driven by input from the CSIRO Mark 2 GCM (with slab ocean) for 20 years of current and doubled CO_2 conditions. Despite a 5 percent decrease in mean annual rainfall over Victoria, extreme rainfall events (50-80 mm/day) with return periods of 5 - 20 years increase in intensity by 20 - 40 percent. The change in extreme rainfall intensity is greater for events with longer return periods, implying even larger increases in the intensity of more-extreme events with return periods exceeding 20 years.

Summary

Increases in heavy rainfall intensity have occurred over the last century in Australia, Japan and the USA, during a period in which global mean temperatures have increased. Concentrations of carbon dioxide and other greenhouse gases are also increasing in the atmosphere. This is expected to lead to global warming and climate change. Climate models can simulate future climate change due to increasing greenhouse gas concentrations. A general increase in heavy rainfall intensity is simulated by coarse resolution global climate models and by fine *(Continued on page 6)*

Hennessy

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resolution regional climate models, with larger increases for more-extreme events. Hence, increases in damage related to heavy rainfall are anticipated due to climate change.

Hughes

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the snow didn't melt during cooler summers, the shift would be in the negative direction, and the ice would thicken. The sea ice may become grounded on the shallow Arctic continental shelf of Asia and North America. Grounded sea ice, called "fast" ice, would cause the draining rivers to flow over the top of the pack ice instead of under it. This could extend over an enormous area. As winter precipitation fell on grounded ice, it would cause the sea ice to become thicker and thicker until it behaved like an ice sheet, advancing on to land and eventually generating its own local climate as Greenland and Antarctica do today. As the area became bigger, local climate would become regional climate and finally would become global climate. This is a long-term process, but once it got started it would be hard to stop. The prospect of forestalling it would be daunting. Could explosives prevent sea ice from grounding, nipping the process in the bud?

Changes in Ice Sheet Mass

NASA has been using laser beams and radar to detect any raising or lowering of the level of ice sheets. In two areas studied, western Greenland flowing into Baffin Bay and Antarctica north of 72 degrees South, both show elevation increasing, in the ball park of 2 - 3 cm, indicating a thickening of the ice sheet. This is despite the many glaciers ringing Greenland and moving toward the sea. One of them, Jakobshavn on the western coast is the fastest moving glacier in the world, advancing at the rate of 8 km a year and producing icebergs the size of a city block which move into the North Atlantic shipping lanes and down to Grand Banks near where the Titanic sank. In other areas of Greenland, the elevation picture is mixed: in some sectors the ice is thinning at 3 cm per year, farther north it is thickening at 6 cm per year and north of that it is thinning at 3 cm per year.

Collapse in West Antarctica

The situation in Antarctica is quite different. The East Antarctic Ice Sheet, grounded above sea level, has been less researched. The West Antarctic Ice Sheet is grounded below sea level, and two-thirds of it has completely collapsed in the Holocene. The jury is still out on just what is happening to the remaining third, but there is one definite conclusion: it is not in equilibrium. Parts of it show net lowering leading to collapse; other parts do not. Actually, very little has been studied; sampling only covers a small area, and a great deal of research remains to be done.

One sample of this area is the Pine Island Glacier which enters Pine Island Bay on the Amundsen side of the West Antarctic Ice Sheet. Its underside is melting rapidly because of greenhouse warming. According to a paper in Geophysical Research Letters of May 1, 1996, by Stanley Jacobs and Hartmut Hellmer of Lamont Doherty Earth Observatory and Adrian Jenkins of the British Antarctic Survey, the underside of this glacier is melting at the rate of 12 meters a year. The entire rise in sea level since the last glacial maximum, spread over 12,000 years, amounts to 120 meters. At the rate of the melting measured by Jacobs et al we could have the equivalent in a decade of the entire sea level rise since the last glacial maximum, as both melting and rising sea level cause retreat of the grounding line for ice sheets grounded below sea level.

The effect of rapid basal melting has been studied by Eric Rignot, working at the Jet Propulsion Laboratory (JPL) in Pasadena. He has shown through satellite imagery that the grounding line of Pine Island Glacier has been retreating at the rate of 5 kilometers in four years. It can be expected to accelerate as the grounding line retreats down an increasingly steep slope.

Pine Island Glacier and Thwaite's Glacier enter Pine Island Bay and together drain one-third of the remaining WAIS. They have been discharging icebergs steadily, with one 100-kilometer iceberg, the size of Connecticut, breaking up in the last 10 years. All around West Antarctica, from the Weddell Sea on both sides of the Antarctic Peninsula to the Ross Sea, enormous crevasses have formed and led to massive outbursts in the last decade. It may be an early warning system for something more dramatic that is just beginning, not merely a coincidence.

Dr. Brenda Hall (University of Maine) is researching the history of the West Antarctic Ice Sheet grounded in the Ross Sea between 8,000 and 6,600 years ago. She found that the grounding and calving front retreated 500 kilometers in the western Ross Sea within a 1400-year interval — geologically an almost instantaneous period. And yet this was a time when ice was flowing into the Ross Sea from both sides. But now, ice is flowing out, into West Antarctica and into the Ross Sea embayment on the east and the Weddell Sea embayment on the west. A retreat in the Amundsen Sea augmented by ice flowing out from both sides could cause the ice sheet to collapse a lot faster than in Hall's historical 1400-year period.

New Ice Stream

In the last decade an enormous ice stream has been discovered in northwest Greenland which no one previously knew existed. It flows northeast from the central dome of Greenland and breaks into outlet glaciers, the main trunk being the Zacharia

Ice Stream. The ice stream is 700 kilometers long, a very long stretch for an ice stream and an indication that it is draining a large area and pulling out a large amount of ice. While the present mass balance is not known, such a large drainage may mean that the positive mass balance of the ice sheet may be switched. If the elevation of the ice sheet is being lowered and the ice dumped into the East Greenland current and into the Greenland and Labrador Seas, both areas of deep water formation for the Conveyor Belt, the implications are extreme. This linkage could yield a very fast response, actually in a matter of days (if the iceberg discharge is large enough).

Work on the Greenland ice core has shown very rapid climate changes in short spaces of time occurring back through geologic ages. The more closely you can sample what is happening, the more distinctly you can resolve the time that elapsed. These changes recorded in the ice core are illustrated by changing dust concentrations and can only show the upper limit of such changes. The changes couldn't have been slower; they might have happened a lot faster.

As we have seen, satellite technology looking at what is happening in the west part of Greenland draining into Baffin Bay, show that the ice elevation is increasing and at the same time sea level rise is also increasing by the same few centimeters. Somewhere the ice surface must be lowering to override the ice surface increases. The likely sites include the West Antarctic Ice Sheet facing the Amundsen Sea and the Greenland drainage basin of the giant ice stream.

The well-documented changes happening just within a decade is a numbing prospect, Hughes says, and we have only hints of exactly what is going on.

Albedo

The ability of ice to reflect solar heat from the earth's surface — known as albedo — cools or warms Earth's surface depending on whether there was an increase or decrease in the amount of Arctic or Antarctic sea ice. Increased sea-ice cover reflects more sunlight, and air temperature is reduced; decreased cover leads to more warmth. Sea ice cover in the polar oceans is an important component of the Earth's climate system. It has a higher albedo than the open ocean and thus modifies the energy balance of the polar regions. It also acts as an insulating blanket, reducing the transfer of heat from the underlying oceans to the cold polar atmosphere.

Perplexing Data

A decline in sea-ice is commonly predicted under global warming, but satellite observations have shown no clear trends. According to a recent Nature article by William K. de la Mare of the Australian Department of the Environment, comparisons between satellite observations and ice-edge charts from early ship records suggest that sea-ice covered a smaller area in the 1970s than during the 1930s, but the observations are seen as "inconclusive." However, details from whaling records which de la Mare has uncovered, including every whale caught since 1931, show that the sea-ice edge moved south 2.8 degrees latitude from the mid 50s to the early 70s. This analysis, based on circumpolar whale catch records averaged over October to April, suggests a decline of about 25 percent in the area covered by sea ice. Such an abrupt change "could imply changes in Antarctic deep-water formation and in biological productivity, both important processes affecting atmospheric CO_2 concentrations."

Other data do not conform with these observations. Satellite obser-

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Hughes

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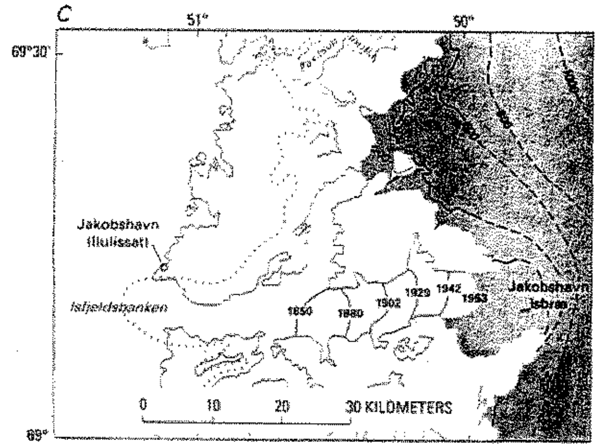
vations only began in 1973, and they show sea-ice coverage has been roughly stable since then, but there is a great deal of regional variability. (In the Bellingshausen Sea, west of the Antarctic Peninsula, there has been a reduction in sea-ice in the past couple of decades.) The fact that the whaling data show abrupt change from 1950 to 1970 and later analysis shows it to appear roughly stable is an "interesting challenge for coupled atmosphere-ocean general circulation models ... and may give insight into fundamental climate processes," say two British Antarctic Survey members who also comment that, "the variability may be natural and not connected to any human-induced changes. But as yet we do not know."

Complete Warming Not Necessary

Earth's albedo also decreases if greenhouse warming disintegrates the floating ice shelves that surround the WAIS. It is not commonly understood that for the floating ice shelves of the WAIS to disintegrate it does not have to warm so much that the ice melts completely, Hughes says. All that is necessary is for some melt water to get into crevasses, which are lines of weakness in the ice shelves. Surface melting exploits the line of weakness, and the surrounding area of the ice sheet can disintegrate without having gone through a longer term melting process.



USGS Professional Paper 1386C, 1995, p.C37

Sketch map of the ice-margin changes around Jakobshavn Ice Stream, 1850 - 1953. Dotted line indicates position about 8,000 years ago.

The snow line, above which precipitation falls as snow, intersects the shelves at a very low angle. Therefore, if climate warming raises the snowline slightly, it can change an ice shelf from having a snow-covered surface to a melting bare-ice surface. This is what happened to the Wordie Ice Shelf on the Antarctic Peninsula. Just a little bit of warming during the summer was enough to change the whole pattern of snow buildup in winter followed by melting in summer. Sea ice is also full of cracks, and so it can disintegrate before it melts.

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