Our Evolving Climate

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I will discuss our understanding of our climate system's recent past, projections for the future and the process leading towards the Fifth Assessment Report from the International Panel on Climate Change (IPCC). The IPCC has been in existence for 20 years, and has produced these reports at 5- to 6-year intervals. These documents are used globally to provide key pieces of evidence for policymakers. And I'll describe what's going on in the area for which I'm responsible in the preparation of the Fifth Assessment Report.

Unequivocal Warming

One of the key statements that came from the last report, published in 2007, is that warming of the climate is unequivocal. The evidence comes from air temperatures, from ocean temperatures—not just from the surface, but also from the body of the ocean—from reductions in the amounts of ice and snow on the surface of the planet, and from changes in sea level because additional water is being stored in the oceans and because the oceans are being warmed. Sea-surface temperature measurements are collected by ships primarily, but also by floats and robots. Although there is a great deal of natural internal variability in the system, we have strong evidence that human activity has been driving these temperatures upwards over the past 100 years.

Composition of the Atmosphere

If we look at the composition of the atmosphere over the past 10,000 years, we would see that something very rapid happened during the past 100 to 150 years in terms of concentrations of key greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The natural variability of CO_2 concentrations—affected by comings and goings of the ice sheets—has been between about 180 and 280 parts per million (ppm), driven by changes in the Earth's orbital parameters. We understand this process well. But, over the past 100 years, the CO_2 concentration has risen by 100 ppm, more or less, above the natural upper limit. That CO_2 has come from our use of fossil fuels and of the land surface, causing movements of carbon from fossil and soil reservoirs into the atmosphere.

In the case of well mixed CO_2 and other greenhouse gases, of which the concentrations are more or less uniform over the surface of the earth, our understanding is high (Fig. 1). On the other hand, in the case of ozone, also a greenhouse gas, our level of understanding is less. Increases in ozone concentrations near the Earth's surface occur, not because we are releasing it but because of other compounds that we are releasing from which atmospheric photochemistry produces ozone as a byproduct. In the stratosphere, manmade ozone interacts with other compounds, lowering the ozone concentration with a small offsetting cooling effect.

Another aspect under discussion is the role of black carbon (Fig. 1)—produced by smokestacks, diesel engines, *etc*.—which decreases the reflectivity of snow, ice and other bright surfaces, causing them to convert more of the incoming sunlight to heat and accelerating the melting of those surfaces. Locally this may significantly affect climate change, although globally it is estimated not to have a huge affect, at least not as described in the current IPCC report.

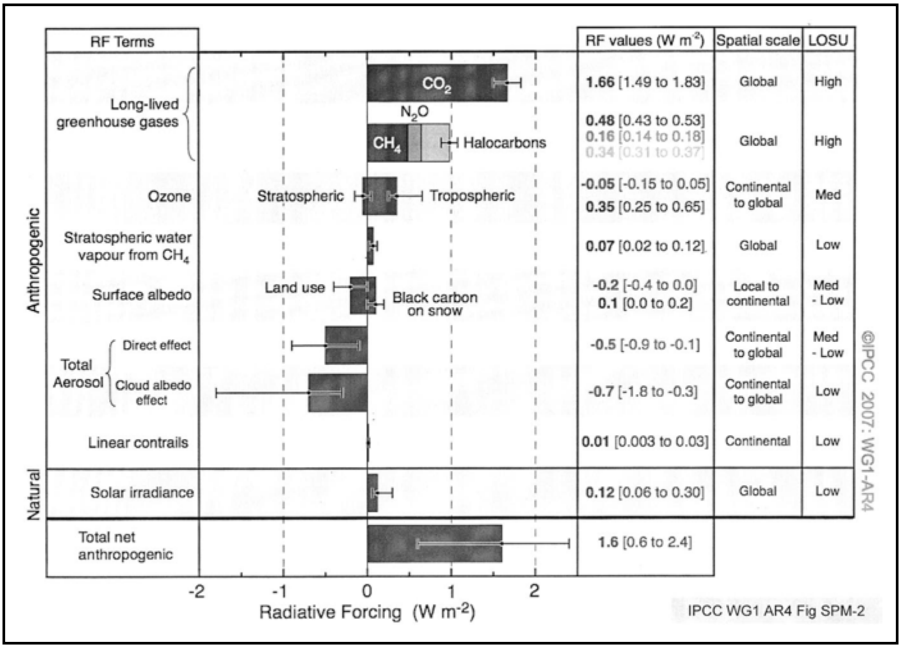

Figure 1. Radiative forcing components (1750–2005).

An area of which we know relatively little has to do with the direct and indirect effects of aerosols that we emit into the atmosphere (Fig. 1). For example, sulfur dioxide from smokestacks is quickly converted to sulfate, which coalesces into droplets. Those droplets reflect incoming sunlight back to space so that less of the sun's energy warms the Earth's surface, which has a cooling effect. These aerosol particles are also thought to have an indirect effect as cloud-condensation nuclei (Fig.1). If there are more of these nuclei around but not more water, the effect is to produce clouds with larger numbers of smaller water droplets, which makes those clouds brighter. Brighter clouds are more reflective and might also be longer-lived. Thus, a cloud of a certain reflectance that exists for a longer period of time, would, of course, have a greater cooling effect on climate. However, in this case, the level of scientific understanding is still quite low.

Forcing Factors

Overall, we can say that the total net anthropogenic effect has been positive since the Industrial Revolution (Fig. 1). One of the ways in which we figure out whether or not these changes are affecting climate is by building computer-simulation models, which we run with the known history of changes in atmospheric composition including concentrations of CO_2 and other long-lived greenhouse gases, occurrence of volcanic events and estimates of change of solar output over time. Accordingly, we can do a pretty good job of reproducing the history of the twentieth century on a global scale by taking into account the effects of human *and* natural external factors on the climate system (Fig. 2a). If we leave out the human factors and include only the natural factors—solar and volcanic forcing—then we cannot explain the rapid warming that occurred during the latter part of the century (Fig. 2b).

The same exercise is possible on smaller scales. However, with respect to Alaska, central North America, eastern North America or Greenland, there is more variability. In the latter part of the twentieth century, divergence between climate-change simulations that include anthropogenic forcing and those that do not is less clear, because, on the smaller scale, it is more difficult to separate forcing effects from internal variability. Nevertheless, the available models are able to provide better explanation of what has happened when anthropogenic forcing is invoked.

We have a pretty strong understanding of what has driven, at least, temperature change over the past 100 years. And I would argue that we have reasonably strong understanding what has driven temperature change on much longer timescales than that.

Projections

Computer simulations of future events use various scenarios for changing greenhouse-gas composition, changing aerosol composition in the atmosphere and so on, over time. For example, we asked the question, “If the CO_2 concentration were to remain constant at the year-2000 level for the following 100 years, what would the eventual warming be?” Models indicate that surface-temperature warming would be approximately 0.1°C per century, which would eventually taper off; in other words, it would take a few centuries for the surface temperature to stabilize at a new level. Ocean temperature or sea-level rise would take a much longer period of time to stabilize.

A certain amount of change is inevitable because the climate system is not at equilibrium with the rate of forcing that it is receiving. If we think of the climate system as a pot of water, almost all of that water is in the ocean and if we set that pot on a stove and turn the burner on a little, eventually it will come to a new steady temperature.

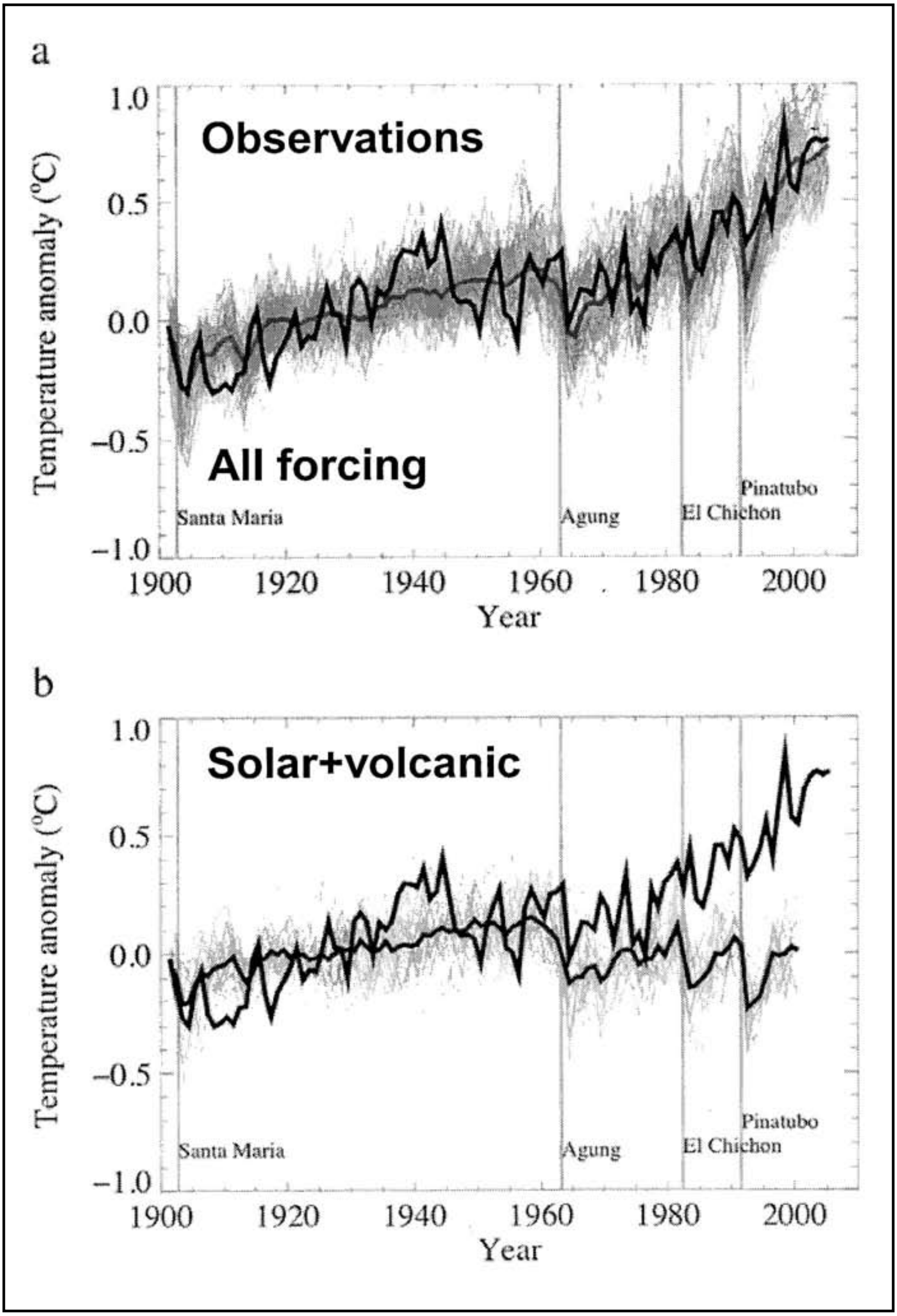

Figure 2. The relative effects of human and external factors on global temperature.

The climate model is essentially a low-resolution weather-forecasting model. The statistics of the variability that climate models produce are similar to the statistics of the variability that we experience in the weather. Medical science learns a lot about humans by studying pigs, and the distance between a climate model and the real system is like that proxy for the human organism compared to ourselves.

The spatial patterns of change predicted by various models are similar because they are determined by where the land is and by what the feedback processes are. These feedback processes are operative at all times, both at low levels of forcing and at high levels of forcing. Therefore, the intensity of these patterns changes but not their specific shape.

Comparing projected precipitation changes of several models occurring when CO_2 atmospheric concentration reaches 750 ppm reveals significant disagreement as to magnitude of change, but better agreement in terms of the sign of the change (*i.e.* whether positive or negative). Comparing projections for North America for summer and winter, it is expected that winters will be wetter and summers will be not only be warmer but also drier, which translates into more crop stress during the growing season.

The IPCC regional diagrams report similar results for annual mean winter and summer temperatures. At the end of the twenty-first century, we expect annual mean warming in North American on the order of 4 degrees, with annual mean moistening but primarily in winter, and drying in summer.

Weather Extremes

One key impact area has to do with precipitation extremes. When I lived in Saskatoon, I learned of the local concern over convective precipitation in summer, and its effects on cars as well as on crops. After a hailstorm we had to return our new vehicle to the dealer to have the dimples taken out.

Figure 3 shows a Canadian climate model, but every similar model would produce a similar diagram. It shows the model's ability to simulate intense precipitation events for the current climate, labeled "1990," averaged over the temperate part of North America. It predicts that a 10-year event would be a 50-mm rainfall within 24 h and a 100-year event would produce approximately 70 mm of precipitation. We know from analyzing the record that the latter is relatively small; however, that is to be expected because the climate models don't have individual convective cells occurring within grid boxes that are removing moisture from layers of air and depositing it on the ground uniformly over large areas such as 100×100 km or 200×200 km. Therefore, we would expect the simulated extremes to be smaller. If you take the 100-year event as simulated by this model and ask how frequently that event will occur towards the middle of the twenty-first century, the answer is about once every 70 or 75 years. And towards the end of the twenty-first century, that event will occur approximately every 50 years. If a storm sewer system is designed to deal with a 100-year event, it means that basement flooding, *etc.*, will occur approximately once per century. Similar flooding may occur every 50 years at some point in the future.

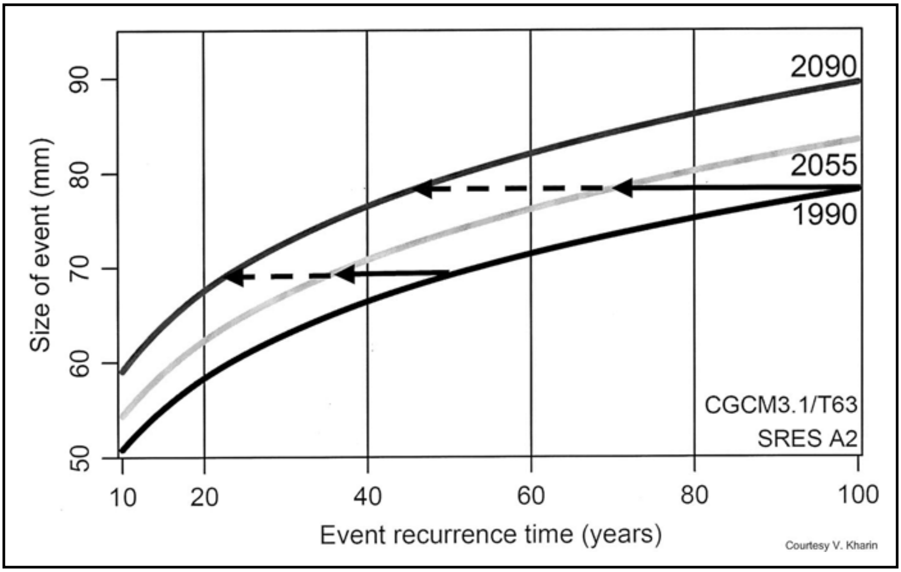

Figure 3. Predictions of 24-h precipitation extremes for North America (25–65°N).

New Forcing Scenario

The IPCC's Fifth Assessment Report will include a new type of forcing scenario called a representative concentration pathway (RCP), which we will provide to models as a prescription for how greenhouse-gas concentrations will change over time, leading to particular levels of forcing at stabilization. As there has been for previous IPCC reports, an international committee is organizing the climate modeling community to run with these new forcing scenarios. Planning for that is well underway and some modeling groups are ready to run with these new forcing scenarios if the experiment includes an attempt to probe the ability of climate models to make CATO predictions—which would be of interest to this community, to be able to plan on the CATO timescale how to undertake changes in hedging behavior, for example, and then also long-term projections for formulation of mitigation policy. These RCP scenarios are aimed at climate models that have active carbon cycles, specifying that there is a certain amount of CO_2 in the atmosphere at a particular period of time, such as 450 ppm in 2050. There will have been a certain pathway to get there, which means that the climate system will have responded with warming and changes in precipitation distribution, with corresponding changes in vegetation because these models will have active terrestrial ecosystems. Responding to the physical and biogeochemical state of the system, the climate model will try to draw CO_2 out of the atmosphere and reduce the 450 ppm. However, the 450 ppm is specified, meaning that there must have been emissions from us, so, by saying what path we are on, we are asking the climate model what emissions are allowed in order to stay on that path. The plan will include a forcing scenario where we actually get to a negative emission scenario by deploying technology that allows us to remove carbon from the atmosphere and sequester it.

Science Informing Mitigation Policy

Figure 4a shows how atmospheric CO_2 concentration varies with latitude and over time, in this case from 1992 to 2001. The rear of the diagram shows CO_2 concentrations near the North Pole at which there is a strong annual cycle. Plants take up lots of carbon in the summer, and the biosphere gives up lots of carbon to the atmosphere in the fall and winter. The annual cycle is reversed in the southern hemisphere, and it's weaker because there is relatively little land there and more ocean, which has a much less-pronounced annual cycle. The general level of CO_2 is increasing over time, which is the part that concerns us, of course, and requires mitigation.

Figure 4b shows our current capability to model this in Canada. It's a global climate model with terrestrial- and ocean-ecosystem components. We told the model what the emissions were during the twentieth century and it is calculating concentrations, tucking carbon away in the right places and producing annual cycles and a general trend that is close to observed. In fact if we start in 1850 with the concentrations as they were then and add what the emissions have been over time, the model correctly produces the year-2000 concentrations. We are making progress here.

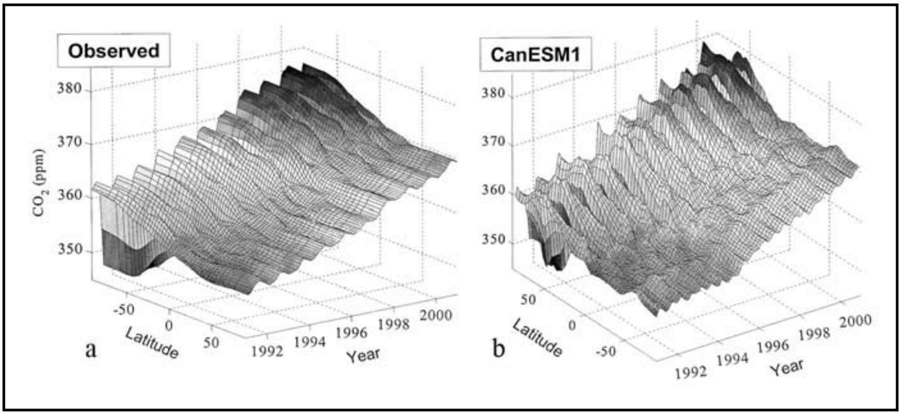

Figure 4. Zonal mean CO_2 concentrations (1992–2001).

Current Emphases

We are also making progress in our ability on shorter time scales. Operating in research mode, we have a coupled atmosphere ocean cryosphere system where we can initialize the ocean from a particular state at a particular point in time and then forecast ahead in time just like making weather forecasts.

We are also developing a new regional climate model for Canada, which is needed to get down to smaller scales that are key for understanding impacts and working out adaptation scenarios. This regional climate model is operated out of Montreal by a consortium, "Ouranos," that is producing continent-scale climate-change simulations. The technology that we use for that is becoming old. In the short term, it will continue to run on computers that are available in Montreal; however, the computing architecture available today is incompatible with how this particular model is constructed, so we are involved in a project to build a new regional climate model for Canada that uses a technology for solving the equations of motion that is amenable to the massively parallel types of machines available today. We are now driving this regional climate model with observations at the moment and will apply it to climate change projections over the next couple of years.

Conclusions

The Fourth Assessment Report, I would argue, tells a compelling story about the causes of past climate change. It provides more clarity and greater policy relevance than previous reports. Furthermore, the language used to relate cause and effect is changing. The Second Report, published in 1996, stated, "The balance of evidence suggests a discernable human influence," so perhaps a little bit better than 50/50. In the Third Assessment Report in 2001, we said, "There is new and stronger evidence that most of the warming of the past 50 years is likely attributable to human activities." "Likely" is a coded word in IPCC parlance, meaning that there is one chance in three that the statement is incorrect, and two chances in three that it is correct. In 2007, a great deal more science was available, with much better understanding of processes. And, of course more data were available. The signal had emerged more strongly and the net effect on the report was that we upgraded "likely" to "very likely," which means that our assessment is that the statement is correct with a probability greater than 0.9, *i.e.* less than one chance in ten that we are pointing at the wrong thing, and likely a much smaller chance than one chance in ten. It's a pretty conservative process.

The Working Group 1 Report that made this statement went through four reviews, which were open to anyone who wished to call her/himself an expert. People on all sides of the debate were able to comment and criticize. Some 30,000 comments were submitted and within the IPCC we developed a process for tracking them. Each comment was recorded. The author teams recorded how they responded to each of those comments, and that dialog is available as part of the public record. Review editors looked over our shoulders to ensure that we were dealing with comments appropriately and in an equitable fashion.

Future changes are inevitable. That means we will need to adapt and need to mitigate and that's a focus of current discussion. Planning of the Fifth Assessment Report is well underway. The scoping meeting for that report will take place in about a month. The new forcing scenarios will be a challenge, but will provide us with opportunities to do more science. There are dual objectives both to inform adaptation on shorter time scales and to inform mitigation on longer time scales. The timeline for getting all this right, and producing a new set of reports, is very tight. Regionalization is going to be a big issue and difficult for us to deal with. However, in Canada we are in pretty good shape in terms of tools to run for the Fifth Assessment Report.

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Dr. Zwiers served for a decade as chief of Canada's premier climate modeling centre, the Canadian Centre for Climate Modelling and Analysis, and, since 2006, he has directed the Climate Research Division within Environment Canada.

He is a fellow of the Royal Society of Canada and has received numerous awards and accolades for scientific excellence and distinguished service.