Handouts for Jan 31, 2008 (SNOW DAY – CANCELLED)

Post to Website, Use in Lecture on Feb 5 2008

This handout draws on excerpts from my Book Chapter which is posted to the 285 Website:

Global Climate Change and the Electric Power Industry

to appear in

Competitive Electricity Markets: Design, Implementation and Performance

2. Global Warming

The world is getting warmer, both in the atmosphere and in the oceans. The year 2005 was the warmest year in over a century, according to a recent NASA report (2006A). Data gathered from 1995 to 2006 have revealed that 11 of the past 12 years have ranked among the 12 warmest years in the instrumental record. Observations since 1961 have shown that the average ocean temperature has increased to depths of at least 3 thousand meters. This warming causes the seawater to expand, thus contributing to rising sea levels (IPCC 2007, p. 4). This section reviews the evidence of global warming, drawing heavily on the reports of the Intergovernmental Panel on Climate Change (IPCC). The IPCC was formed in 1988 and is described in box #1. The clearest and most emphatic statement on global warming appeared in the IPCC's most recent summary for policymakers released in February, 2007:

> *Warming of the climate system is unequivocal,*
> *as is now evident from the observations of increases in global average air and ocean temperatures,*
> *widespread melting of snow and ice, and rising global mean sea level.*
> (IPCC 2007, p. 4)

Box 1. The Intergovernmental Panel on Climate Change

The IPCC was formed in 1988 by the World Meteorological Organization and the United Nations Environmental Program. The 2001 report was the third in a series of assessments of climate change. The summary of the fourth assessment was released on February 2, 2007. The assessments are considered to adhere to a high standard of objective reporting of the science of climate change. The reports must rely on peer-reviewed research, and the summaries must be unanimous, approved by all participating delegates, some of whom serve as representative of their governments. Many view the IPCC as a scientific, consensus-building organization whose reports are conservative and cautious, thus avoiding the tendency to overstate the risks of climate change and the role of anthropogenic emissions. Some scientists believe that the reports understate the extent of climate change because of the modeling assumptions (Hansen 2007, Kerr 2007). Others believe the likely impacts are understated because of the difficulty in describing scientific findings while still achieving consensus from all delegates (Flannery 2005). The IPCC process is slow and difficult, and the reports may not represent the best and latest science. Nevertheless, the reports carry great weight with media and governments precisely because they present a consensus view.

5. Climate Models and Uncertainty

Scientists use a variety of models to keep track of the greenhouse gasses and their impact on the climate, as explained in box #2. Some of the models combine simulations of the atmosphere, soils, biomass and ocean response to anthropogenic emissions. The more developed models include CO2, methane, nitrous oxides and other GHG emissions, and they keep track of their changing concentrations in the atmosphere. The well-developed models also keep track of sulfates (short-lived pollutants which arise primarily from the release of sulfur dioxide from power plants). The sulfates act to reflect sunlight back into space, thereby contributing to the cooling of the planet. Inclusion of the sulfates allowed scientists to explain the "curious enigma" of the 1950s - 1970s. This was a period of rising CO2 in the atmosphere, but the temperature data showed a cooling trend. Climate models helped scientists understand this enigmatic situation when they clarified the role of aerosols in masking the temperature increases that would normally be expected from the rising CO2 concentration.

Box 2. Models of the Climate System

A wide variety of models are used to improve our understanding of climate change. All of the models provide a useful perspective on the highly nonlinear dynamics of the climate system. Claussen (2000) classifies the models according to the degree of complexity: simple, intermediate and comprehensive.

The **simple models** represent the physical concepts in a tutorial fashion. They are sometimes called "box models" since they represent the storage in the system by highly aggregated stocks like those shown in Figure 2. The parameters are usually selected to match the results from more complicated models. The simple models can be simulated faster on the computer, and the results are easier to interpret. This makes them valuable in conducting extensive sensitivity studies and in scenario analysis. A primer on climate modeling and the value of simple models is provided by the IPCC (1997).

The **comprehensive models** are maintained by large research centers, including NASA, NCAR, NOAA, and the Hadley Center in the UK. The term "comprehensive" refers to the goal of capturing all the important processes and simulating them in a highly detailed manner. The models are sometimes called GCMs (General Circulation Models). They can be used to describe circulation in the atmosphere or the ocean. Some models simulate both the ocean and atmospheric circulation in a simultaneous, interacting fashion. They are said to be "coupled general circulation models" (CGCMs) and are considered to be the "most comprehensive" of the models available (Claussen 2000). They are particularly useful when a high spatial resolution is required. However, a disadvantage of the CGCMs is that only a limited number of multi-decadal experiments can be performed even when using the most powerful computers.

Intermediate models help scientists bridge the gap between the simple and the comprehensive models. Claussen (2000) describes eleven models of intermediate complexity. These models aim to "preserve the geographic integrity of the Earth system" while still providing the opportunity for multiple simulations to "explore the parameter space with some completeness. Thus, they are more suitable for assessing uncertainty."

This chapter draws on the results of the Integrated Global Systems Model (IGSM) developed MIT (MIT 2006, Prinn 1999, Reilly 1999). (This is an "intermediate model.")

The IGSM analysis of the uncertainty associated with future climate change (Webster 2003) is particularly useful. The analysis began with an estimate of anthropogenic emissions growing to around 19 GT/year by 2100. The focus of the analysis was the band of uncertainty in future conditions, both the anthropogenic emissions and the climatic effects of those emissions. The mean projection of atmospheric CO2 was around 700 ppmv by 2100. Figures 3A and 3B summarize the MIT analysis. Figure 3A shows the mean result over the century; Figure 3B displays the uncertainty in the CO2 concentration at the end of the century.

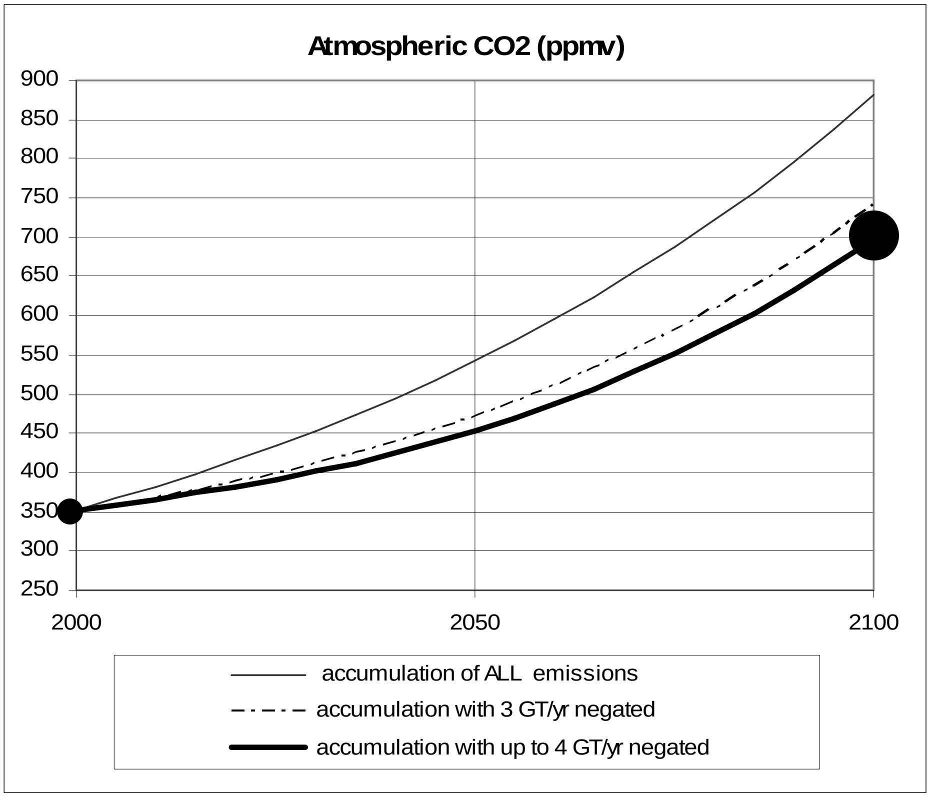

Figure 3A. Accumulations of CO2 in atmosphere with anthropogenic loads growing from 6 to 19 GT/year during the century.
Sources: Author's calculations to interpret the aggregate results published by Webster (2003).

Figure 3A shows atmospheric CO2 growing from 350 to 700 ppmv in a century. The MIT IGSM mean estimate of the temperature impact is a 2.4ºC warming (relative to the temperature in the year 1990). The 2.4ºC of warming is a major impact (i.e., four times higher than the 0.6ºC observed in the previous century.) The 2.4ºC of warming is within the range of estimates by Jim Hansen, Director of NASA's Goddard Institute for Space Studies (Bowen 2006). He predicted that a continued growth of greenhouse gas emissions at current rates would cause global temperature to increase by 2 to 3 ºC in this century. Some readers will be familiar with "equilibrium climate sensitivity," the IPCC term for the temperature impact from a doubling of CO2 concentration. This closely related concept is explained in the box #3.

Box 3. Equilibrium Climate Sensitivity

The temperature impact from a doubling of CO2 concentration is mentioned frequently in IPCC reports. The scientists use the term "equilibrium climate sensitivity" to describe the temperature increase to be expected from a doubling of CO2 concentration relative to the pre-industrial concentration of 280 ppmv. (The impact assumes that the system remains in equilibrium at 560 ppmv.) The IPCC 1990 assessment gave a best estimate of climate sensitivity at 2.5ºC (Houghton 2004, p. 120). The best estimate in their most recent assessment (IPCC 2007, p. 9) was 3ºC with a range from 2 to 4.5ºC. This measure of sensitivity is useful in comparing different models and in comparing the different assessment reports. However, the term is not entirely descriptive of the doubling of CO2 concentration in Figure 3A since the simulation begins the century at 350 ppmv, and the concentration is still growing at the end of the century.

The main purpose of the MIT analysis was to show the uncertainty in the climate impacts. Webster (2003) presented statistical analysis of 250 simulations with uncertainty in the model parameters. (Both the anthropogenic emissions and the impact of those emissions were subject to great uncertainty.) Figure 3B summarizes the statistical analysis by showing the 5%, 50%, 95% estimates of CO2 concentrations and temperature impacts by the end of the century.

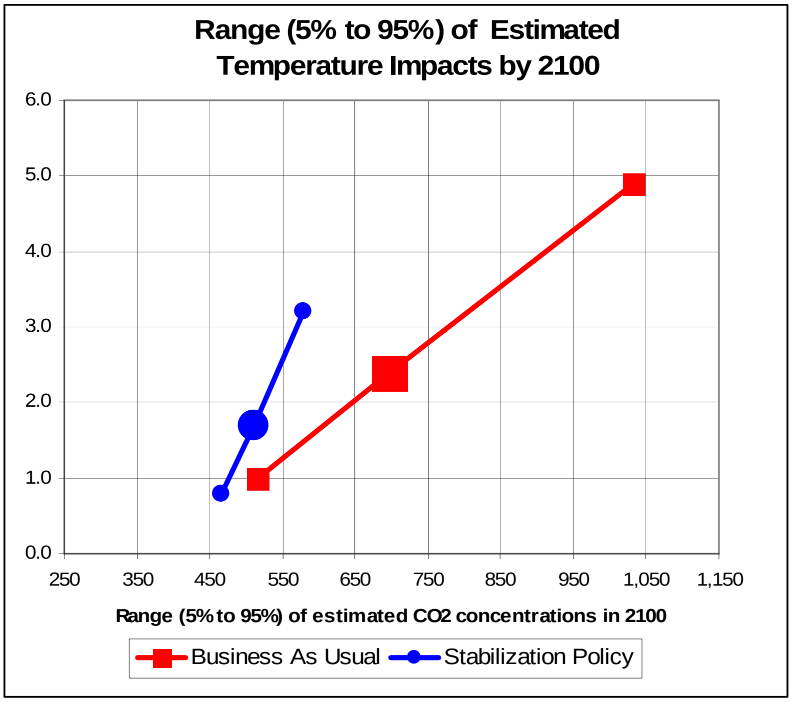

Figure 3B. Summary of the 5%, 50%, 95% range of impacts from Webster (2003).
(The temperature impact is relative to the temperature in 1990).

The “business as usual results” assumes no policy intervention to limit emissions. The most likely result is a CO2 concentration around 700 ppmv and a global average surface temperature 2.4ºC above the temperature in 1990. However, with a policy to control emissions, there would be a cap on emissions with the goal of stabilizing atmospheric CO2 at around 550 ppmv. The most likely result is now a CO2 concentration of 512 ppmv and a global average surface temperature that is 1.7ºC above the temperature in 1990. Figure 3B shows that the 5 to 95% range is greatly reduced with the stabilization policy.

The 5% to 95% uncertainty bands portray the large range of impacts from the uncertain parameters in the MIT model. **But parametric uncertainty is only part of the uncertainty**. **Changes in the fundamental structure of the model could also change the bands of uncertainty.** Examples include the addition of new pollutants (i.e., such as the aerosols mentioned previously) or the inclusion of new feedback effects between the atmospheric and terrestrial systems. These sources of uncertainty are much more difficult to quantify. Ultimately, statements about structural uncertainty come down to the scientists’ intuition on whether the omitted structure will act in a stabilizing or a destabilizing manner. In some cases, adding new relationships to a model will close negative feedback loops which can act to stabilize the simulated system (Ford 1999, Luoma 1991). In many of these cases, the new structure could lead to a narrower band of uncertainty.

However, the customary process of model development is to first include most of the pervasive, well understood, negative feedback loops at work in the system. The less understood feedback loops are often left to future work (when more evidence about their role becomes available.) These omitted feedbacks can often be positive feedback loops that act to destabilize the system, as explained in box #4.

Box 4. Destabilizing Feedback and Rapid Climate Change

A closed chain of cause and effect that act to destabilize a system is sometimes called a positive feedback loop. (The term "positive" comes from control theory. It does not denote that the feedback will lead to changes that are good or bad.) Understanding the role of positive feedback has been crucial to scientists' research and eventual "discovery" of rapid climate change. Weart (2003, 2007) explains that "swings in temperature that were believed in the 1950s to take tens of thousands of years, and in the 1980s to take hundreds of years, were now found to take only decades." Examples of positive feedback loops include:

- methane from permafrost: Higher temperatures can cause the permafrost to shrink, releasing the methane embedded in the clathrate sediments to the atmosphere. More methane in the atmosphere could lead to further warming and still greater shrinking of the permafrost.
- methane from bogs and swamps: Higher temperatures can accelerate the decomposition of dead organic matter in bogs and swamps, also releasing methane to the atmosphere.
- **water vapor:** Higher temperatures lead to more water vapor in the atmosphere which can lead to an increase in long wave absorption. With more absorption, there could be still greater warming and more water vapor in the air.
- **soil decomposition:** Higher temperatures tend to cause faster decomposition of soil carbon, releasing more CO2 into the atmosphere, thus trapping more radiation and increasing the temperature still further.
- sea ice/albedo flip: The sea ice has a higher albedo than the surrounding water. As the ice melts, there is an increase in ice-free water which leads to more heat absorbtion. This increases the polar temperatures causing still further melting of the sea ice.

The water vapor and soil decomposition feedbacks involve a combination of stabilizing and destabilizing feedbacks acting in tandem. With increased water vapor, for example, there may be greater short wave reflection which acts as a stabilizing feedback effect. The relative strength of the water vapor feedback effects is said to be a key factor influencing climate sensitivity (IPCC 2007, p. 9).

The soil decomposition also involves a combination of destabilizing and stabilizing effects. Higher CO2 concentrations can lead to greater biomass growth (due to the "fertilization effect," subject to sufficient nitrogen in the soil to support the growth). This is a stabilizing feedback since increased biomass growth removes CO2 from the atmosphere. Sorting out the relative power of the soil carbon feedbacks requires detailed analysis with "fully coupled" models (Cox 2000, Govindasamy 2005, Jones 2003, Kump 2002). Such analyses show the possibility for soil carbon to change from a net sink to a net source of carbon to the atmosphere. The possible reversal of the net flow from the atmosphere to the soils is a major source of uncertainty in the system, one that is not easily resolved without further research (Govindasamy 2005, Kump 2002).

The destabilizing effect of the sea ice/albedo flip is described in detail by Hansen (2007) and discussed in the news focus editorial by Kerr (2007). Hansen emphasizes the loss of sea ice to make sense of the rapid temperature increases at the terminations of the last two ice ages. He argues that the IPCC models do not represent the amplifying effect of the sea ice feedback and their projections understate the possibility of a rapid rise in sea-level.

IN CLASS ON FEB 5 (if time):

Water Vapor and Clouds

- Draw causal loop diagram on the board to show the (-) and the (+) involved with water vapor and clouds.

- Importance of the Clouds: pp. 629,631,635 of the IPCC report, Climate Models and Their Evaluation,.

Soil Carbon Decomposition

- Draw a causal loop diagram on the board to show the (-) and the (+) loops associated with the increased sequestration and then decomposition of soil carbon.

- Modelers' progress: pp. 5,6,7, abstract of "Feedbacks of Terrestrial Ecosystems to Climate Change."

Conclude with page 15: SURPRISES are to be expected

Rapid climate change is now evident in the past record and is taken as a serious possibility in the future. Weart (2007) cautions that such changes are not necessarily explainable with the main GCMs. Drawing on a National Academy study (NAS 2002), he cautions that "The abrupt changes of the past are not fully explained yet and climate models typically underestimate the size, speed and extent of those changes. Hence, ... climate surprises are to be expected."

Positive feedback effects are difficult to simulate, but their destabilizing effects are important to consider when scientists and policymakers think about the uncertainty of the system. This is why scientists often conclude their quantitative analysis of uncertainty with a qualitative assessment of the possible surprises from relationships that have not yet been simulated in a model. An example is the concluding remarks about the analysis of parametric uncertainty published by Webster (2003, p. 317):

> *As with all investigations of complex and only partially understood systems,*
> *the results presented here must be treated with appropriate caution.*
> *Current knowledge of the stability of the great ice sheets, stability of thermohaline circulation, ecosystem transition dynamics … is limited.*
>
> *Therefore abrupt-changes or 'surprises' not currently evident from model studies,*
> *including our uncertainty studies summarized here, may occur.*

Question for Class: What Kind of Surprises Should We Expect?

The regularly scheduled topic for Feb 5: Other Greenhouse Gasses

Methane (CH4, i.e. natural gas)

The sulfates, the aerosols and the "curious enigma" of the 1950s-1970s