Global Warming

I. Some Background from Climate Science

A. The global warming debate concerns a variety of disagreements about climate science, economics, and politics.

i. One the one hand, there are physical science debates concerning the exact relationship between green house gases and the average temperature of the earth.

ii. On the other hand, there are economic predictions about the long run time path of human emissions of green houses gases (which are necessary to make long term climate predictions) and economic estimates of the damages associated with changes in the earth's average temperature.

iii. These economic effects, in turn, depend in large part on future regulatory decisions by national, state, and local governments, as well as technological advance.

B. There is a body of climate science based on elementary physics that is largely uncontroversial.

i. If the earth has a stable temperature, or has had one, then it must be the case that the energy absorbed from the Sun and produced by the earth itself (via radioactive decay and friction within its core) must be essentially equal to that radiated into space.

- Otherwise the earth would be warming or cooling through time.

ii. Climate models have become increasingly sophisticated in their treatment of radiation and absorption as more complete consideration of air and water circulation have been added to the models.

- There as also been a more sophisticated accounting of the paths through which carbon dioxide is added and subtracted from the atmosphere.
- The circulation of the air and water systems tend to moderate temperature variations on the Earth.
- The circulation of air and water tend to even out the temperatures on earth, although there is still quite a bit of variation around the planet and from decade to decade.
- (For example, the moon is much warmer during the day and colder at night than the earth is.)
- The atmosphere, however, also traps additional heat because of the "green house" effect.

iii. The transfer of energy from the Earth to outer space is affected by a number of variables including the composition of the atmosphere and various air and water currents.

- Some of these factors affect the absorption of the earth.
- Examples include clouds and sulfur dioxide, both of which increase the reflectivity of the atmosphere, and the ice cover which affects the reflectivity of the ground.
- Others affect the rate at which heat is **radiat**ed back into space.
- Examples include vertical winds and, of course, the density of greenhouse gases.
- The most important green house gases is water vapor (by the far the most important), followed by CO_2, Methane, and CFCs.
- See your class notes for discussion of a series of climate models with drawings, arrows, and analysis.

C. It bears noting that naturally occurring green house gases--chiefly water vapor (H_2O), carbon dioxide (CO_2), and Methane (CH4)--cause the earth to be substantially warmer than it would have been without them.

i. Estimates of climate scientists suggest that the average temperature would have been -18^o Celsius rather than + 14^o Celsius without the greenhouse gases that are presently in the atmosphere.

- (The earth is about 58^o Fahrenheit rather than 0^o Fahrenheit because of the green house effect, about 58 degrees F warmer than it would be without it!)

ii. The greenhouse effect has long been present and fortunately so.

- This effect is what makes most of the earth habitable, at our present distance from the Sun.
- When people claim that all climate scientists acknowledge the existence of a greenhouse effect, this is essentially what they mean.
- (It does not mean that all climate scientists believe that human contributions to global warming are about to generate a catastrophe.)
- The United Nation's Intergovernmental Panel on Climate Change (IPCC) has predicted an average global rise in temperature of 1.4°C

(2.5°F) to 5.8°C (10.4°F) between 1990 and 2100, based on the assumption that CO_2 densities will double in that period.

D. Water vapor (H_2O)) is by far the most important of the green house gases and accounts for about 90% of the natural green house effect.

i. Nonetheless, CO_2 gets the most press attention.

ii. This is largely because CO2 is the most important of the green house gases emitted by human activities.

- It accounts for about 70% of the relatively small human impact on the density of green house gases.
- Most of the human induced increase in CO_2 density is from burning fossil fuels.
- This is not because they are carbon-based, but because prior to burning they were buried deep in the ground and so had little or no effect on the density of CO_2 in the air.
- Although densities of other green house gases (methane and CFCs) are also affected by human activity, most of the human induced increases in the density of green house gases are generated by decisions to mine and burn fossil fuels

iii. The estimated effect of increased CO_2 densities on the earth's average temperature varies according to the climate models used.

- Models that assume relatively high positive feed back effects, predict the largest change in temperature from a given change in CO_2 densities. (In such models, increases in CO_2 density are magnified by increases in water vapor density generated by higher temperatures.)
- Models with moderate or no feed back effects yield predictions that are approximately the same as those of the average IPSS panel of climate scientists.
- Models with negative feedback predict the smallest increases in temperatures for a given increase in CO_2 densities. (In these models increases in cloud cover reduce heat gain and increases in vertical winds increase heat transmission back into outer space.)

iv. There is a far wider range of predictions than you would think based on newspaper accounts and coverage of environmentalists.

E. The physics of heat transfer in gases implies that changes in the density of **any** green house gas can change the equilibrium temperature of the earth--other things being equal--by affecting the radiation of energy back into space (the green house effect).

- Changes in the density of greenhouse gases **also occur through natural processes** such as plant decay and volcano eruptions.

F. Less CO_2 tends to be added to the atmosphere from burning fossil fuels than scientists at first predicted, because there are a variety of **carbon sinks** that remove CO_2 from the air and store it.

- For example, plants such as plankton and trees take CO_2 from the air and turn it into plant material (cells).
- Much CO_2 is also dissolved in the planet's oceans.

G. There are also variety of factors (negative feedbacks) that tend to moderate the effect of increases in the density of green house gases.

i. For example, increases in vertical air currents tend to increase the rate at which energy is radiated back into space, reducing the green house effect.

- Water vapor in the form of clouds reflects energy back into space, reducing heat gain.
- (The form that water vapor takes is, thus, critical to the forecasts of climate models.)

ii. These factors imply that the earth maintains a more constant temperature than predicted by many of climate models. (See Lindzen.)

H. There are also a variety of factors that can increase the warming generated through increases in CO2 density.

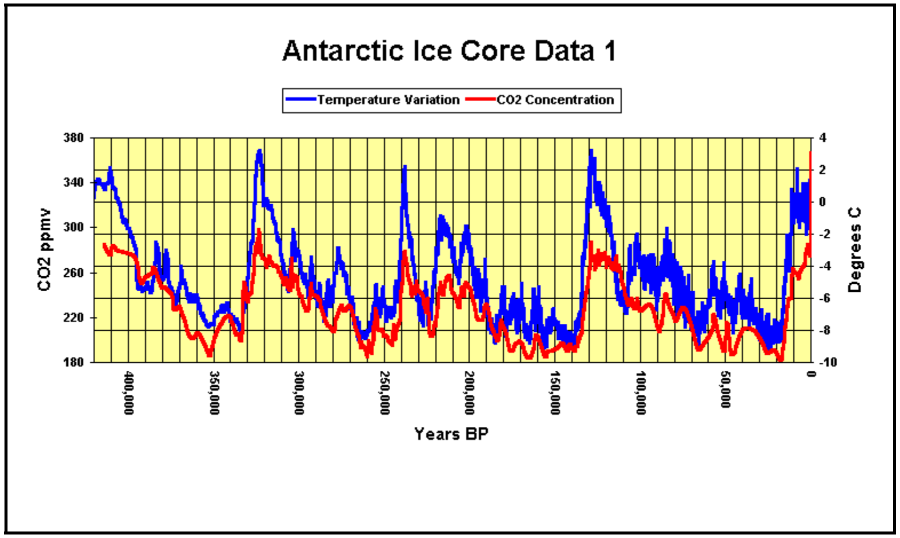
- Higher temperatures tend to increase evaporation and increase water vapor densities in the atmosphere.
- Higher temperature changes tend to reduce the extent to which the tundra and oceans serve as carbon sinks.

I. Overall, in spite of the relatively small **direct** effect of CO_2 densities and the various offsetting effects (clouds and vertical winds) there is a surprisingly high correlation between CO_2 densities and average global temperatures in the long run according to data assembled from ice cores.

- (See the ice core data plot below.)

i. Ice core data is the most extensive record of gas densities and temperature estimates that we have.
   - They allow global temperatures be estimated for several hundred thousand years, although it is not perfect.

ii. Estimated temperatures from ice cored data are highly with CO_2 densities (as shown below).
   -



J. Whether the CO_2 effect on average planet temperatures is large or small, it is clear that the human activities that change the density of green house gases can be regarded as an **externality problem.**

i. Note that to reach this conclusion, we need only assume that the density of CO_2 tends to increase as fossil fuels are burned and that higher temperatures, on net, are undesireable.

ii. However, to determine how **much should be done** about it requires cost benefit analysis of the sort that we have used in class during the semester.
   - (a) This requires estimating the effect of higher $C0_2$ densities on global temperatures
   - (b) the effects of higher global temperatures on plant, animals, humans, and geology (such as ocean depth).
   - (c) whether these effects increase, overall, net benefits or reduce them.
   - (d) the extent to which CO_2 densities are increased by econonic growth.
   - and (e) the extent to which the estimates can be trusted.

iii. The various estimation problems are very difficult to solve, and so a good deal of disagreement can occur among well-meaning scientists at essentially every step in the analysis.
   - The fact that estimation is difficult does not mean that one should ignore all the estimates.
   - One should, however, investigate the assumptions made and take into account that the estimates are uncertain.

II. Economic Development and Global Warming

A. The use of fossil fuels for energy sources is an essential part of contemporary production methods.

i. Clearly, burning fossil fuels puts more carbon dioxide into the atmosphere than has been there recently..
   - CO_2 densities have risen from 280 ppm to about 370 ppm in the past two hundred years.

ii. Increased CO_2 densities along with simple physics implies that Earth's average temperature will increase insofar as it increases the greenhouse effect--other things being equal.

iii. How large the CO_2 effect is depends on climate feedbacks.
   - The most dire predictions assume that higher densities of CO_2 **cause increases in water vapor** density. (CO_2 densities by themselves have a relatively small effect.)
   - The most optimistic forecasts assume that higher densities of CO_2 are largely offset by offsetting feed backs of one kind or another.
   - In general there are models with negative feedback, little or no feedback, and positive feedback.
   - (The little or no feedback models are the mainstream models.)

B. The net effect on the earth's long run average temperature from using fossil fuels depends on a number of factors.

i. **Emissions of CO_2 is a nearly unavoidable consequence of combustion.**

ii. How much carbon dioxide (and other green house gases) are added by reliance on fossil fuels partly depends on the rate at which fossil fuels are used.

iii. The net increase in CO_2 densities also depends on the rates at which CO_2 is removed from the atmosphere by carbon sinks.
- The increase in CO_2 densities observed, is only about half of the total amount that should have been produced by the fossil fuels consumed.
- That is to say, **about half** of the CO_2 gas generated by burning fossil fuels has been removed by from the atmosphere by plant growth (trees and plankton) and by being dissolved in the oceans.

iv. The various places (and processes) at which carbon is removed from the atmosphere and stored are called **carbon sinks**.
- The most important carbon sink is the ocean--not rain forests.
- (See lecture notes on the carbon cycle.)

v. It bears noting that burning wood and other "bio mass" does not add significantly to CO_2 density levels in the same manner, because this part of the carbon supply has long been part of the surface "carbon system" of plant growth and decay.
- (This is why switching to biomass can be one way of reducing the effect of energy production on green house gas density.)
- (Wood remains the main source of biomass energy, although it is a relatively small portion of the energy used in the modern world.)

III. Assessing and Solving the Global Warming Problem

A. In general, **the extent to which global warming is a "problem" depends on a number of factors** as noted above.

i. There are costs and benefits associate with global warming.

ii. There are also costs and benefots associated with various policies that could reduce or eliminate the human component of global warming.
- For example, if only a bit of global warming is induced by increases in CO_2 densities, then there is not much of a problem, and not much should be done.
- If the problem is thought to be severe (catostrophic) then much more aggressive and costly steps can be justsified.

B. The main link between economic development and global warming is through the increased rate of use of fossil fuels that has until recently always been associated with industrialization.

i. Fossil fuels are used because they are relatively inexpensive and portable sources of energy.
- The technology for mining and using fossil fuels are relatively new ones.
- They emerged, for the most part, in the late eighteenth and early nineteenth century.

ii. The industrial age of the past 200 years, consequently, has greatly increased our use of fossil fuels as coal, oil, and natural gas.
- Fossil fuels are our main energy sources.
- They are used to help produce all kinds of things, including transportation, heating, and cooling of buildings, most electricity (world wide), etc.

iii. Other sources of energy do not add "carbon" to above ground carbon cycle, and so they have little or no effect on global warming.
- For example, hydro (dams), nuclear. solar, and wind generation of electricity do not add to green house gas densities.
- Several European countries use nuclear power to produce most of their electricity (as in France and the Netherlands).

iv. So, the link between global warming and economic development is mostly a matter of the relative price of alternative energy sources, rather than growth per se.
- It is **economics that induces "us" to use fossil fuels** rather than other technologies for energy production.
- Fossil fuels are simply "cheaper" and/or more convenient than other energy sources at present.

v. If these relative prices change, there connection between economic development and global warming, if any, may disappear.

C. The key scientific and **policy questions** involve how much warming will occur, where it will occur, and how soon?

i. **First** there is the question of the quantitative link between CO_2 densities and temperature.

- The quantitative evidence on CO_2 and heating, is a bit mixed at present, because temperature increases have not been perfectly correlated with industrialization and the use of fossil fuels.
- (Much of the warming is a bit too early, s**ee the temperature plots from class**.)
- Satellites, tree rings, and ice cores provide some evidence of **human induced** warming that is widely accepted by climate scientists.
- The planet does appear to warmer than it was a hundred and fifty years ago.
- However, there is significant disagreement over "how much" of the recent warming is due to human induced increases in greenhouse gases and how much of that is a consequence of other long term processes (such as solar variation).

ii. **Second, t**here is the economic question of how economic development over the next many decades will affect the emission of green house gases.

- Future emissions can not be known with certainty because technologies may change, because prices of energy sources may change, and because public policies may change.
- Economies have recently become somewhat less energy intensive through time (in terms of btu/$of GDP), partly because of environmental regulations, partly because of technological advance, and partly because of the relative scarcity of oil and natural gas.
- For much of the past 50 years, there has been a tendency to switch to cleaner energy sources--oil for coal, and natural gas for oil--which often reduce CO_2 emissions somewhat along with other more toxic forms of air pollution.
- (The substitution of nuclear power for fossil fuel has largely been blocked by regulations in the US and some Scandanavian countries, although it is extensively used in France and the Netherlands.)

iii. **Third**, there is the economic question of damages.

- How large are the damages associated with temperature changes.
- That is to say, how important is this externality problem?
- Some sense of the importance of the problem is necessary to appraise how much "we" should be willing to pay to reduce it.
- (To answer this question, we must have good reliable climate and economic models, plus a good senses of the distribution of benefits and costs around the world.)
- Most estimates (see for example, Nordhaus) find relatively **small** aggregate damages, **with gains** in the far north and south nearly offsetting losses elsewhere.

D. Disagreement about the answers to these three issues are affected by both scientific uncertainty and ideological disagreements (priors).

i. Model errors tend to larger in the long run than in the short run, at least in economic and political models.

- This is certainly true of economic and political models.

ii. Using middle of the road projections on global warming, still leaves disagreements about the damages done (the magnitude of the externality problem).

- See overheads from the Nordhaus C/B estimates.
- (A significant minority of climate scientists and physicists have suggested that other factors such as variations in solar energy from the sun) are being neglected.)

iii. And, a few have pointed out that the earth has "recently" (past half million years) suffered from a long period of ice ages.

- See Muller's "Icebook".)
- (There are also **national security** reasons and other economic rationales for reducing our use of petroleum.)

E. If we accept the "middle of the road" forecasts, there may well be benefits from reducing the rate of global warming and/or the maximum temperature reached.

i. Note that some of these externality arguments are essentially independent of the size of the externality.

- However, the benefits of reductions in emissions will vary a lot according to the climate theory that one uses for the estimates.
- The costs of such programs tend to rise with reductions in fossil fuel use (more aggressive programs to reduce emissions), and are largely independent of the climate model used.
- The optimal level of emissions (E**) varies with the extent of the damages associate with global warming, which vary with both the climate and economic assumptions used, as in our previous analyses.

F. Within a given country, the emission of green house gases (and the associated global warming problem, however large or small) can be addressed using the same tools as we have already examined for other environmental problems.

- Pigovian taxes (e.g. Carbon taxes)
- Direct Regulation
- Subsidizing non fossil fuel energy sources and/or carbon sinks (e. g. Pigovian subsidies).
- Cap and Trade systems (CO2 emission markets).
- *See previous lecture notes for illustrations with diagrams.*
- As an exercise, represent these problems and solutions with diagrams and game matrices.

i. To reduce US emissions by half requires us to emulate Europe's current policies, because these are about half of US emissions per capita.

- This is largely caused by higher energy taxes (6-8 dollars per gallon of gasoline, etc).

ii. However, it is also caused by a climate that is less variable than that in the US, a much higher population density with many persons living in smaller houses and apartments.

- Higher densities allows cost effective mass transit systems, which are largely already in place and substantially powered by electricity. Shorter distances, also tend to reduce their transportation costs.
- To reach European emission levels per capita will require a somewhat more aggresive policy in the US--e.g. higher gasoline taxes and greater support for non-fossil fuel sources of electricity.

G. If we take the upper range of estimates seriously, more stringent regulations tend to make sense, because the potential damages tend to be greater.

- To reduce net carbon emissions to zero requires either elimination of fossil fuels are a great increase in the capacity of carbon sinks.
- The former might be accomplished by replacing all transport, heating, and cooling with electricity based technologies and by producing electricity via nuclear, hydro, wind, and solar power plants.
- (Clever new artificial carbon sinks might be possible, as with engineered plants, seeding the oceans, or new techniques for increasing the reflectivity of the Earth.)

H. If we take the low end or moderate temperature change estimates seriously, or the low end damage assessments seriously, the externality problem is a relatively small one.

i. In this case, it is certainly possible that the "cure" could be worse than the disease.

ii. (Indeed, one might want to increase CO_2 emissions if one expected a new Ice Age was underway.)

- (Few of us carry umbrellas on bright sunny days, because the cost of carrying the umbrella is greater than the expected reduction in risk.)
- The cost of some regulatory systems can exceed their benefits.

iii. It bears noting, however, that even if today's moderately increasing temperature were entirely a natural phenomena, but could be "adjusted" through public policy, we might still want to attempt to regulate greenhouse gas (net) emissions in some way.

IV. International Treaties as Part of the Solution to Human Induced Climate Change (Kyoto and Beyond)

A. In addition to the usual environmental externality problems, successful efforts to address human induced (anthropogenic) increases in the density of green house gases face a number of other problems associated with "regulatory externalities."

i. The problems are international ones analogous to the regulatory externality examples that we examined in recent weeks.

ii. Each country can rather easily "free ride" on the efforts of other countries to reduce their net greenhouse gas production.

- See the regulatory externality examples in previous lectures.

iii. International treaties will be required to coordinate the greenhouse regulations of all the major producers (and regulators) of green house gases.

- Consequently there will be a variety of enforcement problems.
- And, of course, the agreements themselves may not do very much.
- (See Bjorn Lomborg or Nordhaus on the costs and benefits of implementing the Kyoto accord.)

B. **International solutions** require Coasian contracts (such as the Kyoto treaty negotiated in Japan in 1997.)

- **i.** **National sovereignty** implies that international solutions will be voluntary, and that domestic political and environmental considerations ultimately determine which nations sign and implement the treaties developed.
- **ii.** All the usual problems of relations between governments will obtain.
- **iii.** There will be collective choice problems (what temperature is best?), enforcement problems, free rider problems, and problems of designing institutions to advance international aims.
- **iv.** *Should global temperatures be "selected" by the median voter? by bureaucrats? by new international agencies, through negotiations of national leaders, or by referendum?*

C. Implementing international treaties tends to be problematic, because environmental treaties lack penalties for non-performance.

- **i.** The regulator's dilemma problem does not go away simply because a treaty is signed.
  - Treaties may be cheated on in a number of ways--by interpreting them to be symbolic, by failing to adopt or enforce enabling domestic legislation.
  - These may be insurmountable problems, if the high-damage estimates are correct, since a major shift away from fossil fuels is required in that case.
  - (This makes some of the enhanced carbon sink ideas likely to be the only way to address severe global warming, because this can be implemented by fewer countries.)
- **ii.** Illustration of the Implementation Game after signing a mutually beneficial treaty for pivotal governmental decision makers.

Implementation Dilemma
for International treaties

country A \ country B	fully imp.	partly imp	don't imp.
fully implement	4, 4	2, 5	0, 6
partially implement	5, 2	3, 3	1, 4
don't implement	6, 0	4, 1	2. 2

- **iii.** Note that the Nash Equilibrium will normally be "don't implement," because a country may hope to free ride on the tougher standards adopted by other countries.
- **iv.** Treaties, evidently need some enforcement mechanism to avoid this problem.
  - Show how an enforcement regime might avoid this problem with fines..
  - (Environmental treaties, however, rarely include such provisions. In effect they believe that reputation effects [or good will] are sufficient to induce countries to "live up to" their agreements.)
  - Show how "reputation effects" may produce similar incentive effects.
- **v.** The free-rider problem tends to be more difficult to solve the more persons or more countries have to change their policies.
  - The **politics** of implementing at treaty, however, are clearly significant when domestic costs are large relative to domestic benefits.

D. An important current example: the **Kyoto Protocol**

- **i.** See lecture and web links for details of treaty (differences in constraints/targets)
  - Signatories vs. Ratifiers
  - Modifications -- are heat sink credits "hot air?"
  - Cap and Trade system adopted
  - http://en.wikipedia.org/wiki/Kyoto_Protocol
- **ii.** Kyoto includes no explicit enforcement provisions, and there has been only small reduction in net carbon emissions among signatories so far that have been induced by the treaty.
- **iii.** (See the international treaty handout for more details about Kyoto.)

E. Overall, it is clear that the global warming issue is interesting for many reasons even if it turns out not to threaten the end of life on earth as only a few very high end forecasts predict.

- **i.** Evaluating the expected costs and benefits of global warming raises a number of interesting and important scientific, philosophical, and economic puzzles to be analyzed and resolved.

- Nearly all aspects are worth "a bit more thought" regardless of your intuitions about the magnitude of the effects are or the severity of the problem.

ii. At some point, however, policy decisions will have to be made, and these will have real effects--although not necessarily huge ones on the look of modern life.

- (Cap and trade systems have been on the Congressional agenda for several years now.)

iii. Fortunately, most of the climate models suggest that there is **no immediate crisis**.

- The global warming problem is anticipated to be around for a long time according to the models.
- The cost of addressing the problem increase with delay, but not enormously. (See Nordhaus)
- So, we have some time to figure out what to do and to try to determine how to do what we think should be done.
- As a thought experiment: discuss some of the consideration that would cause you to favor more stringent or less stringent regulations on CO2 emissions or carbon taxes in the US.
- Are any of our policy tools (Coasian contracts, Pigovian taxes, cap and trade, direct regulation, better than current proposals under consideration by the US Congress? Why or Why not?