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Computer Modeling the 20th and 21st Century Climate

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The Historical Beginning of Building Mathematical Models of the Climate System

The actual beginning of building models of the atmosphere and the climate system can be traced to Vihelm Bjerknes, who in 1904 articulated the following principles: “If it is true, as every scientist believes, that subsequent atmospheric states develop from the preceding ones according to physical law, then it is apparent that the necessary and sufficient conditions for the rational solution of forecasting [and associated climate prediction] problems are the following: 1) a sufficiently accurate knowledge of the state of the atmosphere [climate] at the initial time, 2) A sufficiently accurate knowledge of the laws according to which one state of the atmosphere [climate] develops from another.” The square brackets denote my application of Bjerknes’s principles to climate prediction. Although Bjerknes’s words apply to weather prediction, they are still relevant for climate modeling because weather models were the precursors to computer models of the atmospheric, oceans, land-vegetation, and hydrological components which later were coupled and became state-of-the-art climate models. Climate models are rapidly becoming Earth System Models (ESMs) in which biological and chemical cycles are also predicted such as the carbon cycle as well its interactions with the physical state of the climate system.

Figure 1. V. Bjerknes, a Norwegian theoretical Meteorologist, was the first to articulate the basic scientific principles of weather and climate prediction.

Lewis Fry Richardson actually formulated the atmospheric prediction equations into a form that is quite similar to that used in modern weather forecasting models. He performed the first numerical model prediction of weather while on duty in France as an ambulance driver during World War I. Interestingly, he did not want to take part in the battles as a combatant because he was a Quaker with pacifist beliefs so he helped the war effort as part of the Society of Friends who financially supported an ambulance service.[1] Richardson wrote a famous book[2] describing how he performed calculations for the model and the computational problems he encountered. At that time in the 1920s he carried out his calculation with a hand mechanical calculator while waiting between battles. In the latter part of his book he actually outlines how the calculations could be carried out in a parallel and faster fashion very similar to how modern supercomputer systems perform the computations of a state-of-the-art computer model. In Richardson's case he describes a process in which a large number of people perform the calculations with mechanical calculators.

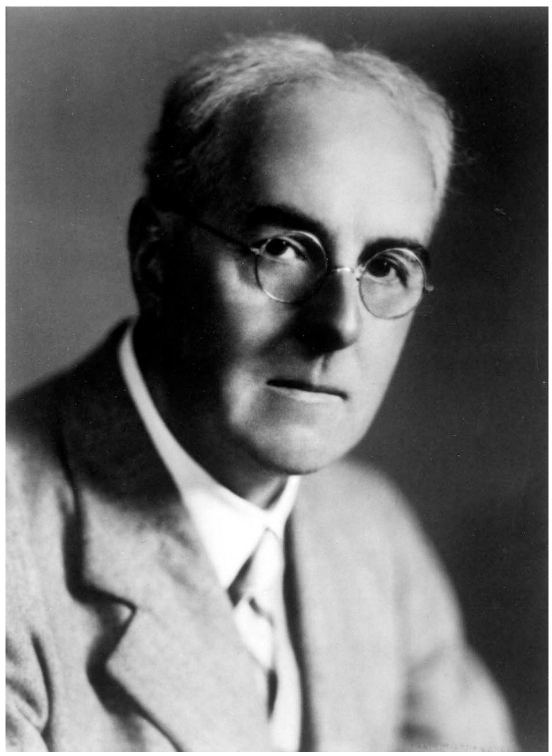

Figure 2. Lewis F. Richardson, the first scientist to attempt a numerical weather forecast of the weather based upon the fundamental laws of physics.

The major task for the last eighty years or so for the climate modeling community has been to follow the dream of pioneers like Bjerknes and Richardson and we are actually

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[1]Hunt, J.C.R. 1993: A General Introduction to the Life and Work of L. F. Richardson, in Collected Papers of Lewis Fry Richardson, Vol. 1 Meteorology and Numerical Analysis, General Editor P. G. Drazin, Cambridge University Press, Great Britain, 1-27.

[2]Richardson, L. F. 1922: Weather Prediction by Numerical Process, Cambridge University Press, reprinted by Dover, New York, 1965, 236 pp.

seeing the dream realized. The modeling community has made spectacular progress, however, there have many been obstacles to overcome and the challenge for the future is to continue on the path of inclusion of more realistic interactive physical processes such as the complexity of clouds and vegetation effects. The modelers are constantly moving to higher resolution models as supercomputers become faster and more capable of solving the mathematical equations. Also, there is a constant searching for more accurate and efficient methods of solving the model equations that govern the climate system.

The famous mathematician John von Neumann of Princeton University's Institute for Advanced Study realized in the mid 1940s that one of the most challenging scientific problems is numerical weather prediction. The Institute had acquired one of the first electronic computers called the ENIAC.[3] The first atmospheric model used on this computer was developed by the science team lead by Jule Charney which designed a model that was much more computational efficient and simpler than that of L. F. Richardson's. The first numerical forecast with the model was a success. A few years later one of members of the Princeton group, Norman Phillips, actually performed the first general circulation model prediction of atmospheric "climate" where instead of a prediction a future state of the weather he put in a crude representation of the forcing of the climate system which was a heating of the "climate" in low latitudes and a cooling in the higher latitudes. This calculation showed the life cycle of storm systems and it was quite successful. This early success led the way for development of more realistic and sophisticated models of the atmosphere which were capable of simulating the high and low sea level pressure weather systems and associated cold and warm fronts that are seen on daily weather maps. Just as importantly the early atmospheric "climate" simulations demonstrated the basic mechanisms that maintain the general circulation of the climate system.

Early Scientific Thoughts about the Greenhouse Effect

There is an interesting analysis of the historical origins of the concept of the greenhouse effect by James Rodger Fleming in his *Historical Perspectives on Climate Change.*[4] This book actually goes into the details of references, misquotes, and misunderstandings. It is clear from Fleming's analysis that the famous mathematician Baron Jean-Baptiste Fourier was the first to suggest the basic concepts in his 1824 paper *Remarques générales.*[5] Fleming points out the following statement is suggestive of the greenhouse effect: "the temperature [of the Earth] can be augmented by the interposition of the atmosphere, because heat in the state of light finds less resistance in penetrating the air, than in repassing into the air when converted into non-luminous heat".[6] Fleming goes into detail about the instrument of Fourier's time called the

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[3]Electronic Numerical Integrator and Computer

[4]Oxford University Press, 1998: *Historical Perspectives on Climate Change*, New York, 194 pp.

[5]Fourier, Joseph, 1824: "*Remarques générales sure les températures du globe terrestre et des espaces planétaires, Ann.cim. phys (*Paris*),* 2nd ser.,27 (1824), 136-167. The English translation can be found in Ebeneser Burgess's *Amer. J. Sci. 32 (1827): 1-20.*

[6]See page Burgess translation on page 13.

heliothermometer or solar thermometer and how Fourier used this instrument to make his inferences. Fourier speaks about luminous heat or light which we now refer to as solar radiation which mostly passes through the mostly "transparent" atmosphere and the terrestrial or infrared radiation that is mostly absorbed by the atmosphere. Thus, Fourier's usage of the term of "non-luminous heat" is infrared radiation in modern terminology.

Svante Arrhenius was the first scientist to raise serious concerns in 1896[7] about increasing carbon dioxide in the atmosphere and its effect on warming the Earth's climate. The reason this was of concern at this time is that in the 1890s the Industrial Revolution was in full swing in Europe and America. One of the main drivers for the revolution was the dramatic increase in the burning of fossil fuels, which at that time, was mostly coal. By simple deduction, Arrhenius knew the surface temperature was dependent on the amount of greenhouse gases. He knew the atmosphere was made up of greenhouse gases such as water vapor and carbon dioxide. Arrhenius inferred that increases of carbon dioxide would mean a warmer planet. Interestingly, Arrhenius estimated in 1896 that an increase of carbon dioxide by 2.5 to 3 times would cause the Earth to warm at the surface by 8 to 9^{o}C, which is a warming not too different from what present day advanced climate models are providing. The comparison is interesting but not really accurate or comparable because Arrhenius's estimate of global warming was based on a very simple calculation without all the complex interactions that are known to exist in the observed climate system and as well as in climate models.

Modern Modeling of the Climate System

One of the principle reasons that climate models have been developed is to explore the past, present, and future climate changes. When we refer to the past climate in this article we are speaking about the 20th century and for the future we are referring to the rest of the 21st century and beyond. It should be added that there is extensive literature on the use of climate models in helping to explain the various paleoclimate periods extending back in time from recent ice ages to the climate of over 4 billion years ago when the Earth was thought to be formed. We will discuss the more recent past climate say from 1870 to the present. This period was picked because we had some limited instrumented measurements of the climate variables such as surface air temperature over parts of the globe at that time. As we go into the 20th century the observed measurement of climate variables in the Earth's atmosphere has increased exponentially. The coverage of in situ and satellite data is far from perfect, however, it is sufficiently extensive enough to give scientists a great deal of knowledge of the various climate mechanisms as well as the trends in the climate system.
There are several questions we try to answer with present day climate models. Can climate models help understand recent climate change? The research community believes they can and that computer models are the most reliable tool for investigating future climate change. Can we verify climate models with observations? The world climate modeling community is continually comparing their models with observations. There are still many difficulties in being able to demonstrate that the models are

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[7]Arrhenius, Svante, 1896: *On the influence of carbonic acid in the air upon the temperature of the ground, Phil. Mag. Ser.* 5, 237.

simulating all of aspects of the climate system correctly. They are certainly capable of simulating essentially all of the first order aspects of climate. Even though there are scientific significant uncertainties, on the whole, the climate model simulations agree well with observations. For example, the models capture with good accuracy the changes of the seasons, the major climatic regional patterns such as precipitation and temperature zones, monsoons, El Niño events and the response to changes in large scale teleconnections with other parts of the globe, jet stream positions and intensity, and mid-latitude storm systems with their related cold and warm fronts. As was briefly mentioned earlier, the atmospheric sciences are very fortunate in that we have enormous amounts of historical in situ and satellite data to compare with our models with in reconstructing the climate from 1870 to the present. Without such data we would not have made progress. We note, however, that there is more limited observational data over parts of the ocean and in the Polar Regions.

Why do model projections of future climate change differ? The exact reasons are still not completely known, however, part of the reasons is that there are differing methods for solving the basic equations and representing the various physical processes such as precipitation and clouds. The modeling community is working closely and collaboratively both nationally and internationally to sort out why computer models give different projections of future climate change. Already we see indications that the cloudiness and its radiative interactions are especially important factors in determining the sensitivity of climate models to increasing concentrations of greenhouse gases and atmospheric aerosols.

At this point, it is useful to analyze the basic aspect of global warming. The term "radiative forcing" at the top of the atmosphere is often used to describe how the climate system will respond to a change in climate forcing. The Earth's climate system absorbs roughly about 70% of the solar radiation that falls upon it. The absorbed solar radiation must be in approximate balance with the infrared radiation that is going out to space at the top of the atmosphere. If there is not a balance of radiative forcing at the top of the atmosphere, the system will be warming or cooling depending on the sign of the imbalance. As greenhouse gases are added to the Earth's atmosphere there is more trapping of the infrared radiation in the lower part of the atmosphere and the overall system must warm up to achieve a new balance at the top of the atmosphere. In this case there is a reduction in the outgoing infrared radiation from the increased greenhouse gases and that is termed the *greenhouse effect.*[8] If we look at two other planets in the solar system such as Mars and Venus, we can see that Mars has very little atmospheric greenhouse gases such as carbon dioxide and water vapor while on the other hand Venus has very high concentrations of greenhouse gases. Mars has a surface temperature of the -50^{o}C and Venus 420^{o}C. Of course Mars is further from the sun and the Venus is closer to the sun. Thus, the radiative forcing for the two planets is a combination of the solar forcing difference and the amount of greenhouse gases that determine the basic surface temperature for each of the planets. For the same solar forcing the amount of greenhouse gases largely determines to first order accuracy the surface temperature. The Earth's atmosphere has both carbon dioxide and water vapor

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[8] Ramanathan V. and Tim Barnett, 2003: Experimenting with Earth, *Wilson Quarterly (http://wwics.si.edu/index.cfm?fuseaction=wq.print&essay_id=33085&stoplayout=true)*. Published by the Woodrow Wilson International Center for Scholars.

as the major radiative forcings for greenhouse gases and they along with the solar flux absorbed in the atmosphere largely determine how warm the planet becomes.[9] As the carbon dioxide concentration increases the system starts to warm up and water vapor content of the atmosphere also increases. This water vapor increase is a strong positive feedback on the climate system. The addition of the increased greenhouse gases from 1870 to the present represents about a 2.5 watts per square meter (Wm^{-2}) imbalance at the top of the atmosphere.

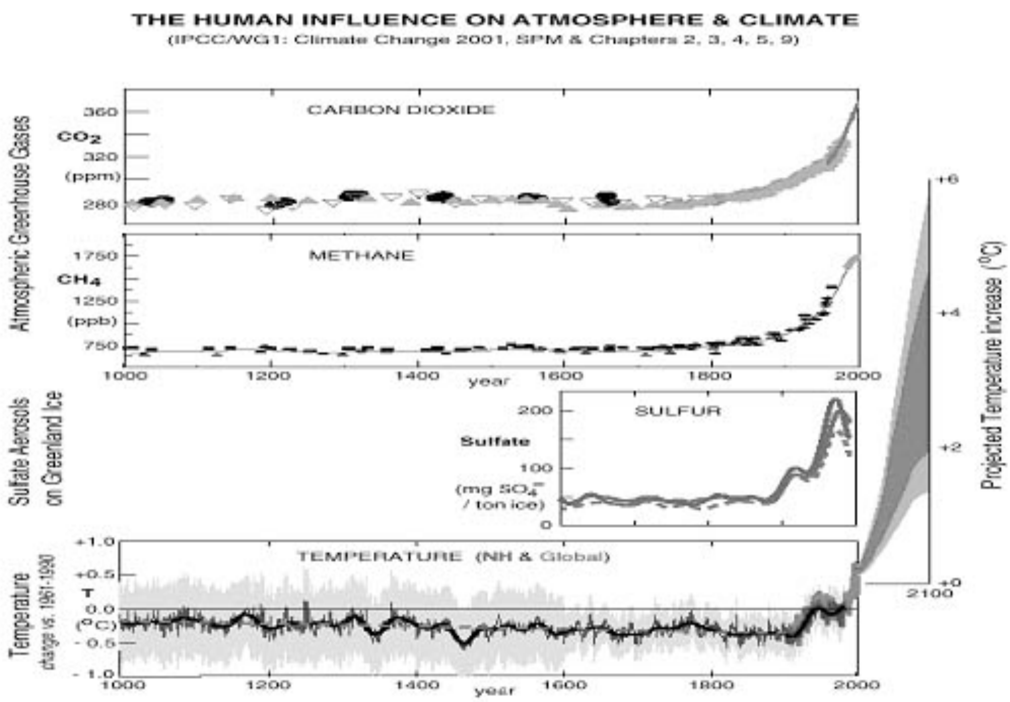

Figure 3. Global averaged carbon dioxide, methane, sulfate aerosols, and temperatures are shown as a function of time. Michael Prather prepared this figure from IPCC (2001) data.

Recent Climate Change Over the Last Millennium and the Future

Figure 3 shows the changes in carbon dioxide (CO_2) atmospheric concentration from a thousand years ago to the present. It can easily be seen in the figure that there is a rapid carbon dioxide increase in the last part of the 20th century. The measurement of past carbon dioxide concentrations comes from air bubbles trapped in the ice cores at the time the snow fell and ice formed. The ice cores are taken from the large ice sheets of Greenland and Antarctica. In the same ice core are other greenhouse gases such as methane and nitrous oxide which have less effect but still show a more significant increase along with the carbon dioxide. At the bottom of the graph is shown the surface air temperatures over the last thousand years. During most recent times after the 1860s there are worldwide direct instrumental measurements of temperature and for time before 1860 or so tree rings and coral sediments proxy data are used (see Mann et al.

[9] Ibid. 78. Ramananthan and Barnett point out that chlorofluorocarbons (CFCs), halocarbons, methane, and Nitrous oxide account for 40% of the total the Earth's anthropogenic greenhouse effect.

1999)[10]. The proxy data is calibrated by using the instrumental record time period for establishing correlations. This figure shows that the period in the last 30–50 years is unusually warm. Mann et al. (2003)[11] later showed that this temperature record can be extended back to 2000 years, so we have an excellent indication that the late 20th century warming is remarkably different. More recently several researchers have tried to construct similar proxy temperature records like Mann et al. and they obtain similar graphs that show the last 20th century warming is the largest over the past millennium. It should be pointed out that this is an area of active research and not all studies agree. On the far right side of Figure 3 are future projections of surface air temperature from several climate models. These projections come from an assessment of the Intergovernmental Panel on Climate Change (IPCC, 2001)[12] which is comprised of a large group of international scientists. Note that there is a substantial spread of projections. The world community is trying to find out why some models are more or less sensitive to increasing greenhouse gases and other climate forcings. In spite of the uncertainty, it is clear that the climate will be warming significantly. Figure 3 also shows the changes of sulfate aerosol concentrations with time. In the latter part of the century, the concentrations have decreased due to emission controls on power plants. The sulfate aerosols act to regionally cool the climate system but their impact is usually less than the warming effect of increased greenhouse gases. Interestingly, as we clean the air of pollutant aerosols the cooling effect of aerosols will lessen and that could cause the greenhouse effect to increase.

Essentially all climate models are showing that there is substantial warming that is likely to take place between now and the year 2100. The 21st century projected sea ice and snow distributions dramatically shrink in terms of horizontal size as well as thickness. Glaciers around the world and polar sea ice have rapidly melted during the 20th century which causes a strong positive feedback due to the lower albedo or reflectance of the Earth's surface. This in turn causes increased heating of the surface especially in the higher latitudes. Thus it is expected that the melting rate over snow and sea ice areas will increase in the 21st century.

Contemporary Climate Models are Becoming Earth System Models

At this point, it is useful to examine what is in contemporary climate models as shown in Figure 4. As can be seen in the figure there are atmospheric, ocean, sea ice and land cover components of climate system represented in schematic fashion. Within the atmospheric component there are land and vegetation processes as well as snow, soil moisture, and river transport. The latter brings fresh water to the oceans to complete the water cycle. Both detailed solar and infrared radiation and its interaction with clouds and convection are also included. Some of the climate models include some aspects of

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[10] Mann, M.E., Bradley, R.S. and Hughes, M.K., Northern Hemisphere Temperatures during the Past Millennium: Inferences, Uncertainties, and Limitations, *Geophysical Research Letters*, 26, 759-762, 1999.

[11] Mann, M.E., Jones, P.D., Global surface temperature over the past two millennia, *Geophysical Research Letters*, 30 (15), 1820, doi: 10.1029/2003GL017814, 2003.

[12] IPCC, 2001, Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report. Houghton, J.T. and co-editors, Cambridge University Press, Cambridge, United Kingdom and New York, 881 pp.

ecology and biogeochemistry although this aspect of climate is undergoing rapid development. See Washington and Parkinson (2005) for an introduction to three-dimensional climate modeling.[13]

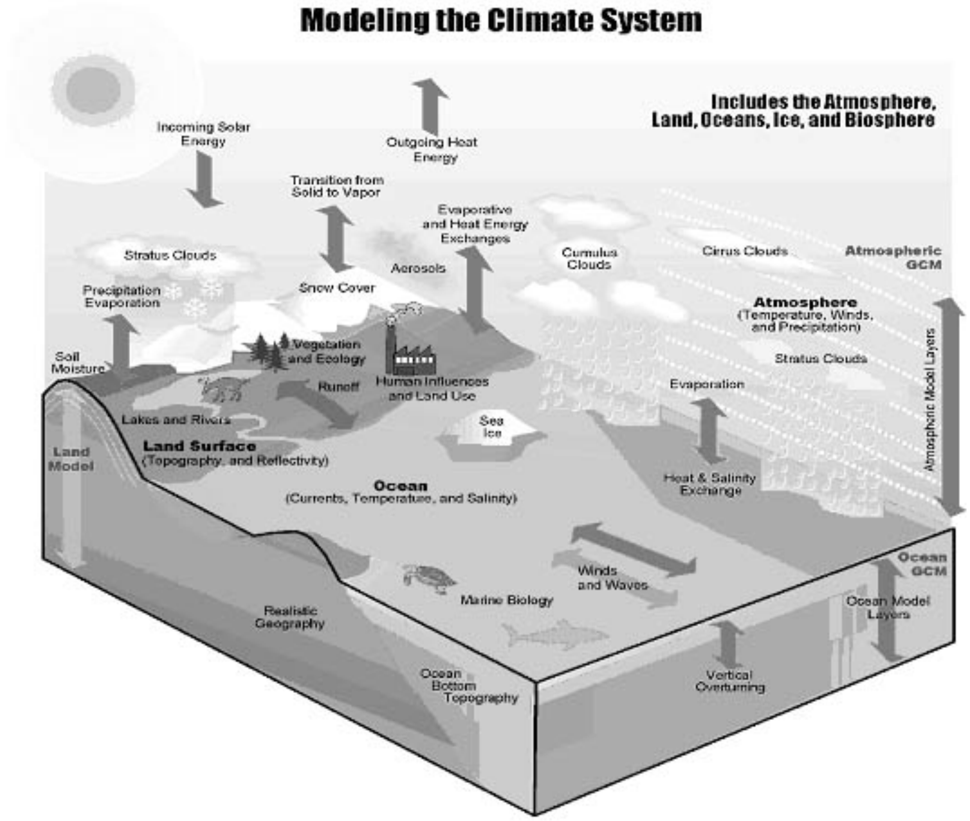

Figure 4. This is a schematic of the various components and interactions of a state-of-art climate model. This particular schematic was produced for the NCAR Community Climate System Model.

As mentioned earlier in the article, present day climate models simulate virtually all of the principal climate features. Recently there have been some exploratory high resolution global simulations by scientists using the Japan's Earth Simulator supercomputer, which is the world's fastest computer that is available to the climate modeling community. With such a computational tool it is possible to perform few limited very high resolution (10 km) global atmospheric model simulations. At such resolutions realistic hurricanes form that are embedded in the global model. The simulated hurricanes, or as they are called in Asia, typhoons even have open centers much like those in nature. Furthermore high-resolution ocean and sea ice models also show very realistic small scale features such as Gulf Stream eddies. So we know that we are clearly on the right track and that we are restricted by the speed and capability of available supercomputer systems.

[13]Washington, W. M. and C. L. Parkinson, 2005: An Introduction to Three-Dimensional Climate Modeling, 2nd Edition, University Science Book, Mill Valley, California, 355 pp.

Natural versus Anthropogenic Climate Change

There is an ongoing controversy about whether mankind is changing the climate system. Are changes that we are observing only natural variations in the climate system?

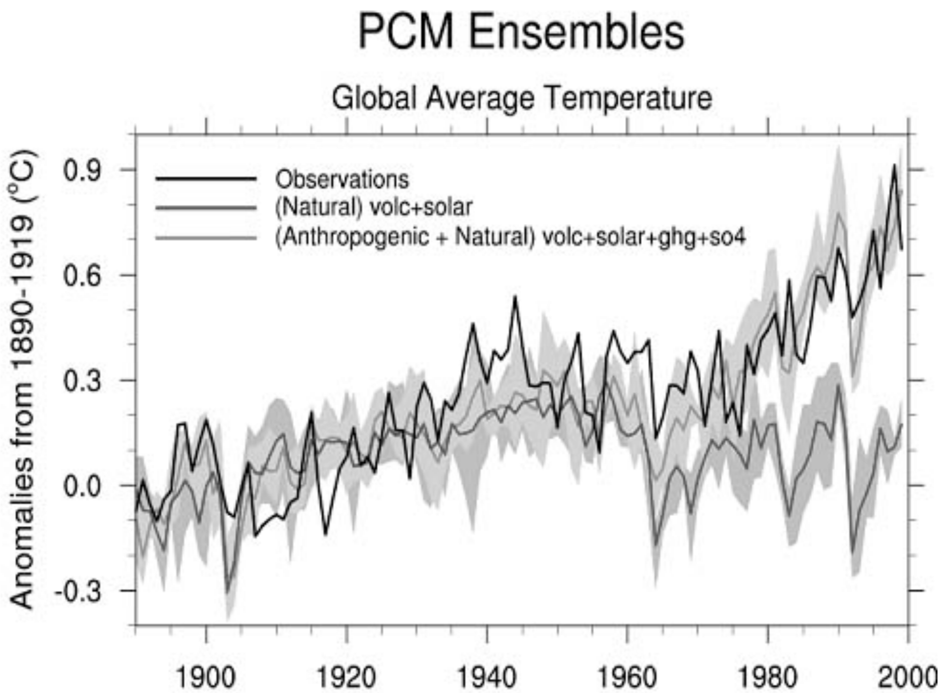

Figure 5. Ensemble simulations from DOE supported Parallel Climate Model. Shown are observed 1870 to 2000 global observed temperatures (heavy black line), natural climate forcing from volcanic eruptions and solar changes (medium dark line); and anthropogenic climate forcing from increasing greenhouse gases and sulfate aerosols (lighter dark line). The shaded are the range of five member ensemble of simulations. (See Meehl et al. 2004 for more details)[14].

In Figure 5 we show observations and model simulations from 1870 to the 2000 from the NCAR/U.S. Department of Energy Parallel Climate Model (PCM) (Washington et al, 2000)[15]. The natural forcings of the climate system are volcanic and solar variations. Note the natural forcing simulations in the figure explain the early part of the 20th century temperature change. When the anthropogenic increase in greenhouse gases and sulfate aerosols is added to the natural forcings, the simulations show a general pattern of warming that closely follows the observed. The solar forcing seems to be the predominant factor in the early part of the century and in the latter part of century the largest factor is the increasing greenhouse gases. The sulfate aerosols have a smaller

[14] Meehl, G.A., W.M. Washington, J.M. Arblaster and A. Hu, 2004: Factors affecting climate sensitivity in global coupled models. *J. Climate*, **17**, 1584-1596.

[15] Washington, W.M., J.W. Weatherly, G.A. Meehl, A.J. Semtner, Jr., T.W. Bettge, A.P. Craig, W.G. Strand, Jr., J.M. Arblaster, V.B. Wayland, R. James, Y. Zhang, 2000: Parallel climate model (PCM) control and transient simulations *Clim. Dyn.*, **16**, 755-774.

cooling effect. It is possible to identify individual volcanic cooling events of about 18 months; for example, the 1991 Pinatubo eruption cooling event is well simulated and it compares favorably with the observed cooling.

A small number of scientists are skeptical of global warming. Clearly different points of view must be taken seriously by the scientific community to see if they are valid. Most of the controversy concerns estimates of satellite measurements of lower atmospheric temperature. Earlier satellite measurements showed little agreement with in situ balloon based observations of the late 20th century.[16] More recent estimates by researchers show a warming trend in the lower atmosphere that is in closer agreement to climate model simulations. Another area of skepticism is whether land cover changes can account for the observed surface warming. This too is an area of uncertainty, however, preliminary analysis indicates that this is a relatively small effect compared to the greenhouse effect and there is ample evidence that the surface ocean temperatures have warmed significantly since the 1950s.

Summary

To sum up what we generally know about global warming I would like to quote from the Intergovernmental Panel on Climate Change (IPCC, 2001):[17] "An increasing body of observations gives a collective picture of a warming world and other changes in the climate system." This assessment involved hundreds of scientists. The average global temperature has increased in the 20th century by 0.6 degrees. The last decade of the 20th century is the warmest decade in the past two millennia.

The future climate modeling research priorities include understanding why models give different projections of future climate change and the lowering of uncertainties about the role of atmospheric aerosols. We are starting to combine biogeochemistry processes into our climate models – carbon, sulfate, and nitrogen cycles. It is anticipated that these additional aspects of the climate system will become a standard part of more complete Earth System Models. Because climate models have limited resolution, we cannot provide detailed information on regional climate change which is what the public and policymakers want. Figure 6 shows several resolutions of climate models that have been and will be used for further studies.

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[16]National Academy Press, 2000: Reconciling Observations of Global Temperature Change, 104pp. A more detailed analysis of differences can be found at the IPCC following report http://www.grida.no/climate/ipcc_tar/wg1/060.htm.

[17]IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report. Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J. and Xiaosu, D., editors. Cambridge University Press, Cambridge, United Kingdom and New York. 881 pp.

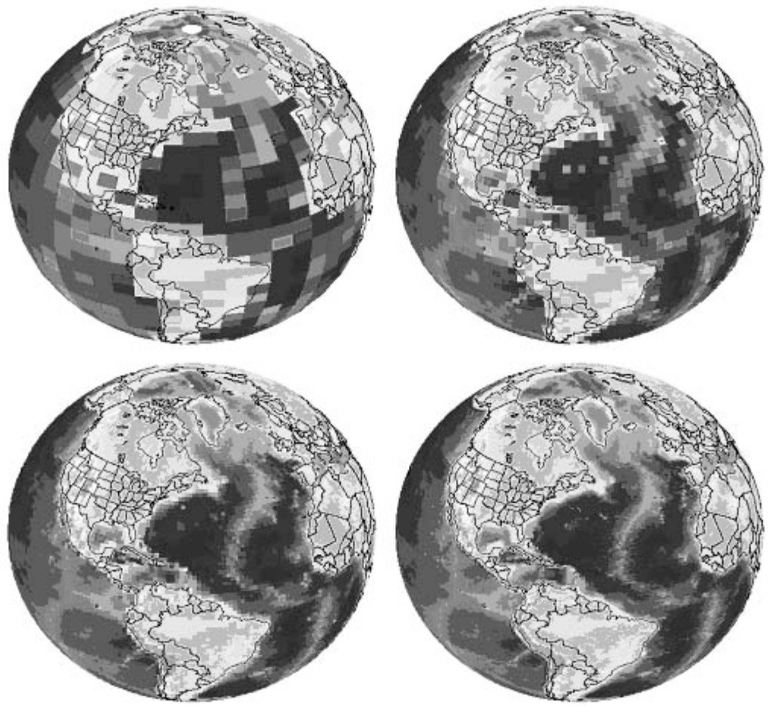

Figure 6. This is a figure of typical atmosphere and ocean model resolutions. The upper left is a resolution consistent with 1960s to 1980s where grid size is about 500 km. In the 1990s we use the upper right resolution of about 300 km and lower right is about early 21st century were resolution is 150 km. The lower right resolution is about 75 km. Note with increasing resolution in the mountains, coastal regions, and ocean bottom the climate simulations become closer to reality. This figure was prepared by Gary Strand of NCAR.

As we acquire more powerful supercomputer systems we will be able to provide significantly improved regional predictions of climate change; however we still need to improve our treatment of physical processes such as clouds. This will require additional special observational studies. We are rapidly improving hydrological aspects of our models. The reason for this is the increasing concerns of whether there will be adequate water resources, especially in the Western United States and other parts of the world. As the climate changes it has been documented that the health of ecological systems worldwide has gotten worse. Only part of this is caused by climate change. Population pressures and overuse of resources are also large factors. The recent status of ecological systems throughout the world has been reported in the 2005 United Nations Millennium Ecosystem Assessment.[18] In this report there is extensive analysis of the global food, fiber, fresh water, and energy needs for a growing population. Already there are stresses on the ecological systems that must be dealt with if the planet is to remain reasonably habitable. Future Earth System Models will need a strongly integrated ecological component that takes into account these complex systems.

[18] http://www.maweb.org/en/products.aspx.

It is likely that both mitigation and adaptation strategies to climate change will be required as part of the solution. Climate models can provide information of the various options and give insights about whether and how to geoengineer the climate system. That may seem like an obscene phrase to use – "*geoengineering the planet*" – but we are already changing the climate system, and if we are going to be changing it more we need to think about not only the ethical aspects of controlling the climate, but also what will be the impacts. Changes in one region of the globe can effect change in other regions.

Near term climate change is inevitable. Even if the greenhouse gas concentrations are held fixed the climate will still be changing to adjust to a new climate state. Thus the climate system is "committed" to change even if greenhouse gas concentrations are curbed.[19] The reason that the system is committed is because with the increased greenhouse gases the climate system has an imbalance that we referred to earlier. The only way the system comes back into balance is by warming the lower part of atmosphere and the Earth's surface. Warming of the ocean at deeper depths will take longer. The overall process will take several centuries. However, if the greenhouse gas concentrations are decreased rapidly then the balance at the top of the atmosphere will be closer to balance and the overall climate system will not continue to warm. We also need to think about government policies that will yield the most optimum effect. Any solution requires an intergenerational policy. At what point do we as nation or internationally get serious about geoengineering? As you recall from my earlier remarks, the globally average temperature has warmed 0.6 degrees centigrade over the last century with most of warming taking place in the polar region particularly in the Arctic region[20] where it has caused significant changes in the climate. What happens if the climate warms at say one degree per decade? I would imagine at that point the nations of the world will, finally, get very serious about climate change, and drastic steps will have to be taken. Government policymakers have great difficulty dealing with intergenerational problems such as climate change especially if the policies cause some immediate sacrifice. The only way to avoid this is for policymakers to explicitly prepare the public and other nations for the need. This is true leadership for a policymaker. The fact that the United States has decided to not be part of the Kyoto climate change protocol is a case in point. Although the Kyoto agreement had several problems, that in itself is not a sufficient reason to refuse to sign. Most international agreements undergo significant changes as more is learned about "the problems". So as time goes on such agreements improve in their effectiveness. The scientific problem of global warming is easier to solve when it is small rather than large. It is time for policymakers to be "leaders" on this important problem. Benjamin Franklin had an appropriate quote that can be applied to the world's dilemma - "When the well's dry, we know the worth of water."[21]

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[19]Meehl G. A. , W. M. Washington, W. D. Collins, J. M. Arblaster, A. Hu, L. E. Buja, W. G. Strand. H. Teng, 2005: How Much More Global Warming and Sea Level Rise? SCIENCE Vol. 307, 1769-1772.

[20]Corell, R. and Co-Authors, 2004: Arctic Climate Impact Assessment, Cambridge University Press, 144 pp. and http://www.acia.uaf.edu/.

[21]From Benjamin Franklin's Poor Richard's Almanac.

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