SIXTH ANNUAL JOHN H. CHAFEE MEMORIAL LECTURE
ON SCIENCE AND THE ENVIRONMENT

January 26, 2006

Finding Climate Change and Being Useful

Dr. Ralph J. Cicerone
President, National Academy of Sciences

National Council for Science and the Environment
Improving the scientific basis for environmental decisionmaking

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Finding Climate Change and Being Useful

Dr. Ralph J. Cicerone

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Sponsored by the

National Council for Science and the Environment (NCSE)

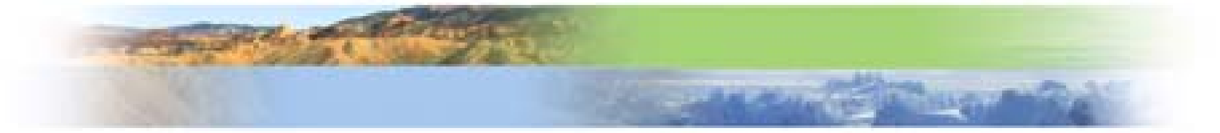
Presented at the

6th National Conference on Science, Policy and the Environment

Ronald Reagan Building and International Trade Center in Washington, DC

January 26, 2006

This volume is the sixth in a series of books documenting the annual John H. Chafee Memorial Lecture on Science and the Environment.



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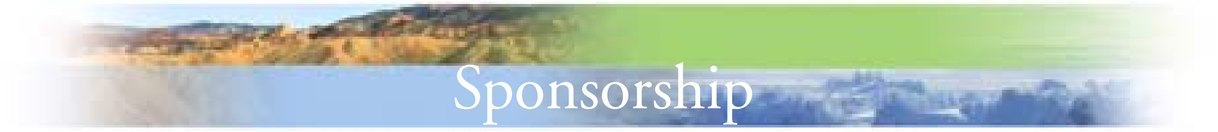

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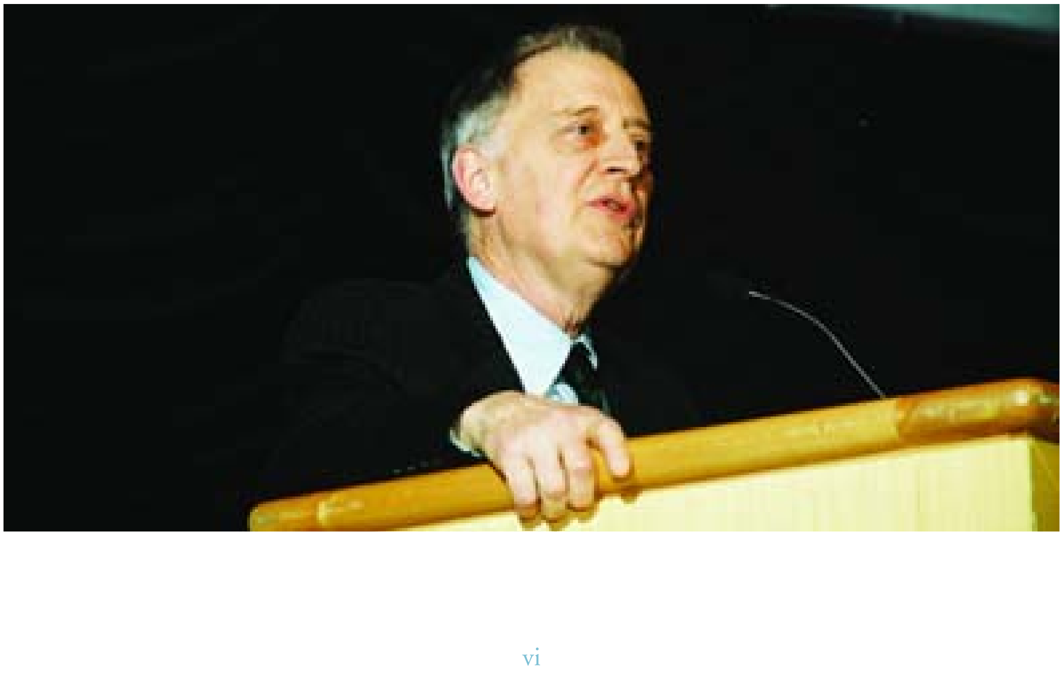
Dedication

This book is dedicated to the memory of Senator John H. Chafee who, in his 23 years representing Rhode Island in the U.S. Senate, was a leader in promoting a bipartisan, science-based approach to environmental issues.

Top: Participants at NCSE's 6th National Conference on Science, *Policy and the Environment:* Energy for a Sustainable and Secure Future.
Bottom: *Dr. Ralph Cicerone delivers the Sixth Annual John H. Chafee Memorial Lecture on Science and the Environment:* Finding Climate Change and Being Useful.
Right: *Dr. Cicerone and his wife, Carol, at the reception following his lecture.*



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Introduction

Ambassador Richard Benedick, President, NCSE

Ladies and gentlemen, every year a highlight of the National Conference is the John H. Chafee Memorial Lecture on Science and the Environment. The list of past speakers is most impressive: Nobel Laureates Sherwood Rowland and Mario Molina, Pulitzer Prize winners E.O. Wilson and Jared Diamond, National Science Foundation Director Rita Colwell, and environmental statesman and corporate leader William Ruckelshaus.

Tonight, we have added another luminary to this constellation of stars. Fittingly, he is a scientist — a super-scientist, I would say — whose work in stratospheric chemistry proved critical in the history of protecting the ozone layer. That subject was of crucial interest to Senator John Chafee, for whom this lecture is named. When Senator Chafee became a champion for the Montreal Protocol in 1987, at a time when I was the chief U.S. negotiator, the proposed treaty had come under heavy fire from ideologues within the Reagan Administration who wanted to reverse the U.S. position for strong controls over ozone depleting chemicals. In the face of this opposition, John Chafee became a powerful voice in the Senate for a strong ozone treaty.

It was the courageous and far-sighted efforts of Senator Chafee, together with a bipartisan coalition of other senators including Max Baucus, Al Gore, and the late John Heinz, and also Secretary of State George Shultz and some brilliant scientists such as our laureate tonight, that eventually helped to preserve the precious ozone layer. Because of their stand, President Reagan overruled some of his closest advisors — and incidentally, did not yield to their wish to fire me as his chief negotiator. Ronald Reagan in fact became the first Head of State to personally endorse a strong ozone treaty, a treaty that he characterized as a "monumental achievement of science and diplomacy." The treaty was subsequently ratified by a bipartisan vote in the U.S. Senate of 95 to nothing. Ladies and gentlemen, tell this to your children, tell your students — weren't those really the "good old days"?

Ralph Cicerone was one of the first scientists who, over 30 years ago, warned of possible dangers to the stratospheric ozone layer — a thin layer of molecules, 30 to 50 miles above where we are now sitting, that protects all life on Earth from potentially fatal ultraviolet radiation. Dr.

Cicerone's research was formally recognized by the Nobel Prize Committee in its citation for the 1995 Nobel Prize in chemistry to Sherwood Roland. In 1999, the Franklin Institute recognized Ralph's critical contributions to the understanding of greenhouse gases and ozone-depleting substances by awarding him one of the most prestigious of American science awards — the Bower Award and Prize for Achievement in Science. He has received numerous other distinguished awards, including the 2002 Roger Revelle Medal of the American Geophysical Union and the World Cultural Council's Albert Einstein World Award in Science.

Ralph Cicerone earned his Bachelor's Degree in Electrical Engineering from the Massachusetts Institute of Technology, where, I'm delighted to observe, he was also a varsity baseball player. Ralph, what position did you play? He's waving...he probably played pitcher ... or maybe catcher? Pitcher it is — I guessed that: mental telepathy! A quintessentially American sport and a quintessentially American scientist. He went on for his master's and doctorate at the University of Illinois.

His early career was at the University of Michigan and then the Scripps Institute of Oceanography at the University of California, San Diego. Later, he was Director of the Atmospheric Chemistry Division at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. It was there that I first met him in person, although I already knew of his path-breaking research when I was negotiating the treaty. In 1988, I had the good fortune of being appointed a visiting fellow at NCAR in order to work on my book on the Montreal Protocol, *Ozone Diplomacy*.

For a layman, those days at NCAR were like a marvelous dream. Under the tutelage of legendary scientists, like our laureate this evening and Walter Roberts, Dan Albritton, Susan Solomon, and others, I was able to develop the means to describe in my book for an interested lay public the scientific underpinnings for the negotiation of this historic treaty. I remember in particular a summer lunch outdoors against a backdrop of the Rocky Mountains, when Ralph Cicerone and others tried to explain to me the mysteries of the Antarctic "ozone hole."

The ozone hole was a totally unpredicted seasonal collapse of the ozone layer over a huge area around the South Pole, which began to be recorded in the early 1980s during the Antarctic springtime — September and October at those latitudes. At the time, the causes were unknown: it could have been chlorine from manmade chemicals, or it might have been a natural phenomenon. One theory (eventually the correct one) was that chlorine was indeed the culprit and that it was activated by something called "heterogeneous chemistry." (Ralph, I hope I don't mess this up and that I finally did get this straight!) This is an arcane process in which gases that have become solidified on some kind of a platform — in this case, particles of polar ice — can interact in a violent chain reaction just when powerful radiation from the sun, which emerges in the spring, begins to release the chlorine from its icy grip.

Well, I pondered this difficult concept during that lunchtime tutorial. I grappled with it over a lamb chop, and then I asked the scientists whether this heterogeneous chemistry could also occur elsewhere in the atmosphere — not necessarily on ice flakes over the South Pole, but perhaps also on tiny particles resulting from industrial pollution? Because if this happened, it could thereby cause not just the gradual slow depletion of the protective ozone layer that was predicted in the theoretical models, but rather a fatal collapse that would affect not just penguins in Antarctica, but also the heavily populated mid-latitudes of our planet.

In the ensuing conversation, I was reassured that such a catastrophe was unlikely to occur because industrial particles are rained out in the lower atmosphere before they reach an altitude where radiation is sufficiently strong to cause the reaction. But after some further discussion, Ralph Cicerone intervened, "Wait a minute; it might be theoretically possible for a powerful volcanic eruption to propel minute particles so high into the stratosphere that a rapid ozone-destroying reaction could indeed occur."

Several months later, Ralph was quoted in *The New York Times* (it was either from Senate testimony or a scientific paper) as characterizing the volcano danger as "a potential bombshell" — and I subsequently cited this in *Ozone Diplomacy*. I tell this anecdote to illustrate not only the warm collegiality of scientists like Ralph Cicerone, but also as an encouragement for us non-scientists and students in the audience. I know that we have some students here today, so please take note: don't hesitate to ask seemingly naïve questions of brilliant scientists, because scientists love to explain things to the interested non-scientist, and this can be a rewarding experience for both sides.

After NCAR, Ralph Cicerone went on to the University of California, Irvine, as the Daniel Aldrich Professor of Earth System Sciences. And in 1998, he became Chancellor of that great university.

Ladies and gentlemen, we are truly in the company tonight of one of the planet's premiere scientists. And it is my honor to introduce the 2006 John H. Chafee Memorial Lecturer — the President of the National Academy of Sciences, Dr. Ralph Cicerone.

JOHN H. CHAFEE LECTURE MEMORIAL LECTURE
ON SCIENCE AND THE ENVIRONMENT

Finding Climate Change and Being Useful

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Finding Climate Change and Being Useful

JOHN H. CHAFEE MEMORIAL LECTURE ON SCIENCE AND THE ENVIRONMENT

It's a great honor and pleasure for me to be here, as it would be for anyone. Ambassador Richard Benedick sets the standard for all of us with his depth of knowledge, his creativity, and his effectiveness, which I think explains the respect with which all of us hold him in our own minds.

There's a saying in show business that you should never get on a stage after a child performance or a dog act. And at a conference like this, to take the podium after Russell Train has had it, and in the memory of John Chafee, I think it's an analogous situation that no one should try. But nonetheless, whatever the show is, it's going to go on, and I will try to deliver the lecture without being overawed by the memory of John Chafee, the wonderful stories about Senator Stafford, and the lifetime achievement award (for a career that continues) to Russell Train.

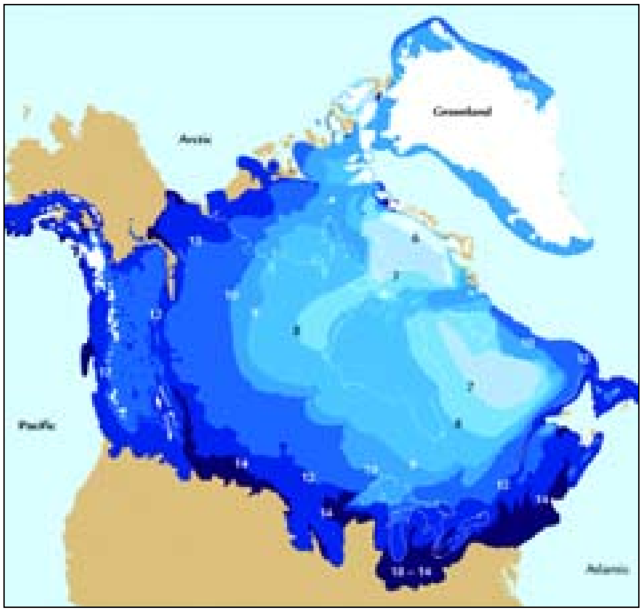


Figure 1. Reconstruction of the extent of ice cover during the last ice age (from Ruddiman et. al. , 2005). Numbered contours indicate the geographical extent of ice cover N thousand years ago.

Tonight, with the title *Finding Climate Change and Being Useful*, I'm going to talk about detecting climate change, and that it has been done, whether we wanted it or not. And then at the end I will add a few words about being useful.

First of all, as to the very idea of detecting climate change inside of one human lifetime, we shouldn't forget how difficult that is. We know that there have been many climate changes in the Earth's history before now, and there will probably be continuing climate change, with or without human presence. These previous changes are not completely understood, but as one depiction, Figure 1 shows a reconstruction of historical ice extent over North America during the last glacial maximum, 18,000 years ago.

You will see from this figure that the southern extent of the ice went through the Middle Atlantic region of the United States and deep into the Midwest 18,000 and 14,000 years ago. And then as the ice began to recede, 12,000, 10,000, 9,000 years ago, there was still very, very deep ice over parts of Canada and the upper northwestern states. These reconstructions are based on several kinds of evidence from geologists and geographers. This image exemplifies that climate change has occurred often throughout the planet's history and that some epochs of large change continued over thousands of years, so that detecting climate change within one human lifetime is a difficult job.

Figure 2 is a photo from a 1979 cover of *Science* magazine, which I chose for two reasons. It shows an inland glacier, the Quelccaya Glacier in Peru, photographed and explored and measured by Lonnie Thompson, who is a hero in this business because of his intrepid expeditions to high altitudes. If you look closely, you can see the strata, the layers of ice that are essentially annual layers. They are exposed in this photograph, as they usually are not, because the edges of glaciers don't usually look like this and they are not so accessible. By careful studies of layers like these from ice formations from Greenland and Antarctica, scientists have been able to construct climate histories.

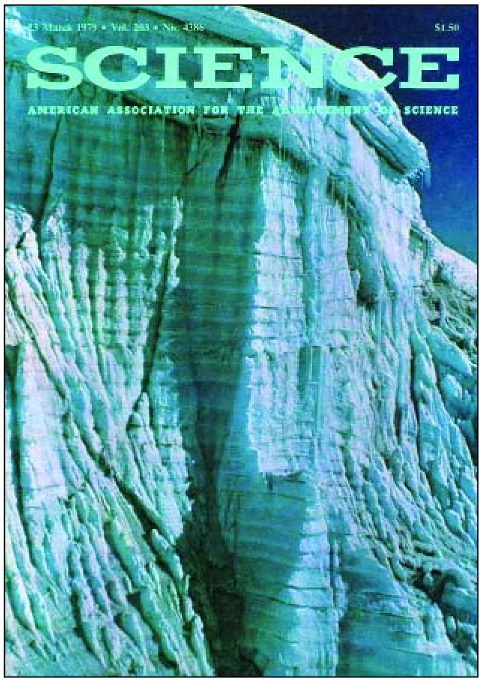


*Figure 2. **A photograph of the Quelccaya ice cap in Peru (from Thompson,1979). Annual bands of ice are visible in this photograph taken in 1979.***

By dating those annual layers and by extracting chemicals from inside such layers, histories of the chemical composition of air have been deduced back to 700,000 years ago; I will show you some data later.

Going back further than 20,000 years ago into paleoclimate, there is evidence of previous cold periods on Earth and, of course, of warmer periods in between. There were apparently times when the polar regions, at least, were much warmer.

Let us now move to contemporary times. Figure 3 is a graph of surface temperature measurements (from thermometers) since about 1880. This particular data set is from the NASA center in New York City; there are several similar data sets where a couple of hundred million data points will go into creating a curve like this. There is a five-year running mean in red, and annual mean temperatures are shown with black squares. The data shown are temperature anomalies; that is, temperature differences measured from a reference point. The particular zero reference point is the mean value between the years 1950 and 1980. So, above zero means warmer than the period 1950 to 1980 and below zero means cooler. These data are globally averaged annual or five year averages. The temperatures are taken from the different latitude belts of the Earth, continental regions, and ocean regions and averaged according to the area-weighted latitude belt that they are in — a proper global average, after excluding obvious effects from cities (the urban heat-island effect). There are historical records showing that thermometers measuring temperatures of regions undisturbed by cities that were later overtaken by urban spread produced contaminated temperature records after that point. Those kinds of data have been removed. Figure 3 shows global averages, as far away from cities as you can get.

There are several interesting features of Figure 3. One striking feature is the record of the last 25 or 30 years, since the late 1970s. This is the fastest temperature rise (or fall) recorded in the instrumental record. The last 25 or 30 years are most notable for two reasons; I will mention one reason now and one later. This rapid rise of temperatures is faster than can be regenerated in any of our climate models, and the total warming from the 1950 to 1980 baseline is larger than can be explained by existing theories — unless we include the human-enhanced greenhouse effect. The rapid warming since the late 1970's is just as clear in the southern hemisphere (which is mostly ocean and less contaminated in various ways).

This recent warming is statistically very significant (several standard deviations above the noise), and its rate exceeds any natural variability that we can understand mechanistically. And it is faster than any of our computer models can generate from first principles. The total warming since 1880-1890 has been 0.8 to 0.9 degrees C, with more than half of it since the late 1970's. The cooling between 1940 and 1975 was strongest in northern mid- and high latitudes and might have been due to reflection of sunlight from airborne particles due to sulfur pollution (from burning high sulfur-content fossil fuels); see Charlson et.al. (1990) and Santer et. al. (1995).

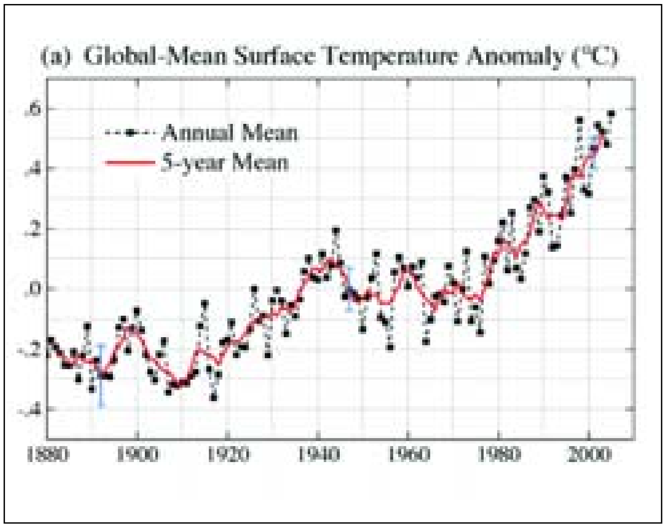


Figure 3. Surface temperatures averaged over Earth's surface, graphed as the difference from the global average temperature of 1950 to 1980. Measurement methods, locations, and data handling are described in NASA, 2006, and references therein.

What happened before 1880? Some very good scientists have worked hard to reconstruct temperatures of the times before the Industrial Revolution, before there were thermometers. Figure 4 summarizes several such attempts to reconstruct northern hemisphere temperatures going back 2,000 years.

These reconstructions are based on tree rings, geological bore holes, coral samples, stable isotopes in various reservoirs, and some historical accounts. The instrumental record (data like those of Figure 3) is the green curve on the upper graph on the extreme right. Temperatures of the last 25 or 30 years are higher than those reconstructed for the past 500 years, and probably above those of the past 1,000 years. Reconstructing past temperatures is an active area of research, as is setting confidence limits on the ranges of temperatures in various geographic regions over the past 1,000 or 2,000 years, so the data of (and conclusions from) Figure 4, especially those from years prior to 1500 A.D., are less precise than those from Figure 3.

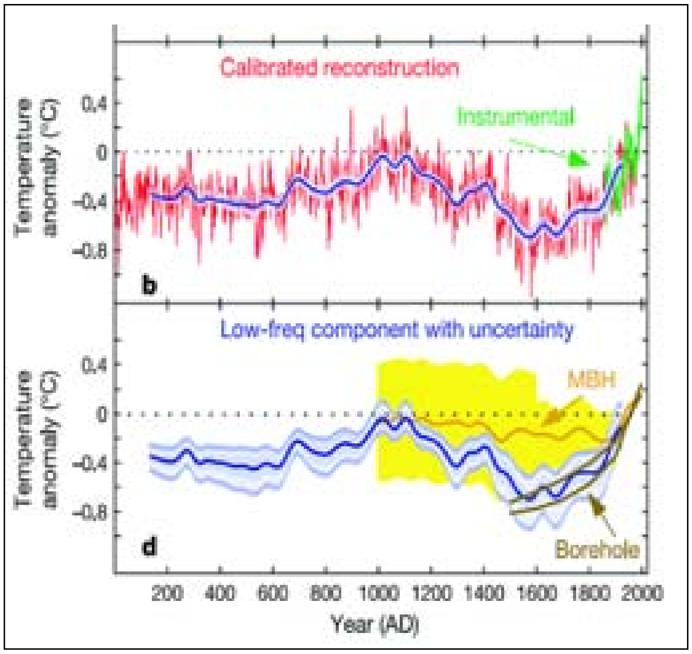


Figure 4. ***Estimates of Northern Hemisphere temperatures over the past 2,000 years, reconstructed from various proxy indicators. The top graph includes temperature records from thermometers, similar to those of Figure 3. Ranges of estimates and the meaning of shaded areas are explained in the original reference (Moberg et.al. 2005).***

Several other notable pieces of evidence have emerged to show us that climate is changing. For example, recent years of ocean data show a similar warming. One such study reported a careful analysis of ocean temperatures and the heat content of the oceans above the thermocline, that is, the top 700 meters or so of the ocean's waters (see Figure 5).

The increased heat content of the waters (heat capacity multiplied by temperature increase multiplied by amount of heated water) turns out to equal the extra heat due to the greenhouse gas trapping of heat in the Earth's surface over the same period predicted by climate models (Hansen et. al. 2005).

Figure 6 presents observed temperature-profile changes (from 1960 through 1999) in various ocean basins and compares them with corresponding profiles calculated through considerations of physical oceanography and heat exchange from the atmosphere. The authors (Barnett et. al. 2005) could reproduce the actual temperature profiles (represented by the red circles on the graphs of Figure 6 in all of these different ocean basins) by including the warming from the human-caused greenhouse effect. Similar calculations assuming only a change in strength of the sun's illumination itself could not match the observations,

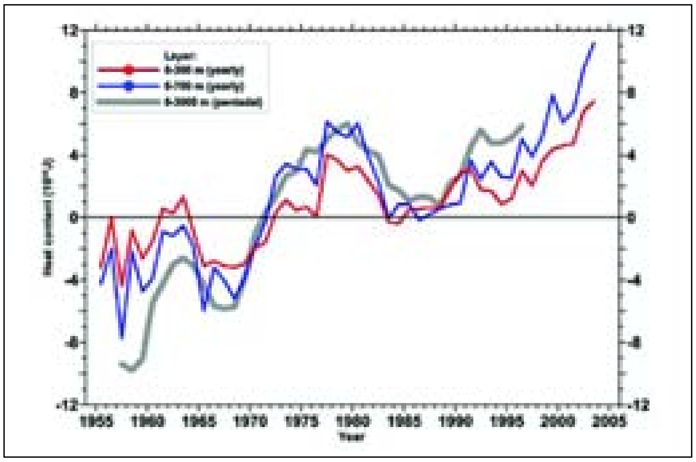


Figure 5. Time series of yearly ocean heat content (10^{22} J) for the 0-300 and 0-700 m layers and pentadal (5-year running composites for 1955-1959 through 1994-1998) ocean heat content (10^{22} J) for the 0-3,000 m layer. Each yearly estimate is plotted at the midpoint of the year; each pentadal estimate is plotted at the midpoint of the 5-year period (from Levitus et.al. (2005)).

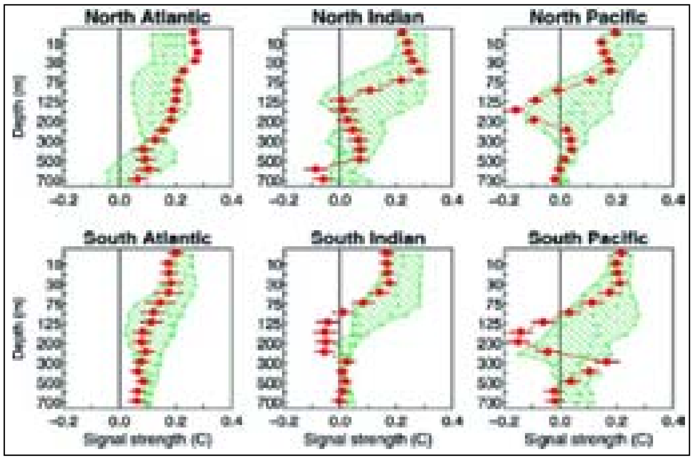


Figure 6. Observed and calculated changes in oceanic temperature profiles versus depth for the period 1960-1999 from Barnett et. al. (2005). Red circles: observed warming signal strength. Green hatched area: range of signal strengths in PCM model with anthropogenic forcing included.

which I will discuss a little more later.

There has been some pronounced warming in the Arctic. Figure 7 shows observed temperature increases of the last 50 years, on a two-dimensional representation of the spherical globe. On this kind of projection, the very top of the graphs, going from left to right is 90 degrees north (the North Pole) and the very bottom of each figure going from left to right is 90 degrees south. The temperature coding (false color images) is at the bottom; reddish brown indicates a temperature increase (annual average) of almost three degrees Centigrade and on the left, light blue indicates an annual average temperature decrease of 0.5 degrees. Contours of temperature increases have been drawn from actual temperature observations. Largest warmings have occurred in Alaska, Siberia, and the Antarctic Peninsula. Most ocean areas have warmed. The remote location of most warming makes it clear that the warming is not a product of local urban influence.

This very rapid warming of the Arctic region is not fully understood yet, but climate models do predict more warming in the polar regions than anywhere else. Also, although not shown in this figure, the warming is more pronounced in the winter than in the summer. There are, in fact, a couple of small spots that are showing slight cooling in spots here and there around the Arctic. But generally, large warmings, melting of ice, melting of snow pack, and thawing of permafrost have been observed.

Figure 8 shows a set of remote sensing images. In the upper depiction, the 1979 summertime sea-ice extent appears as seen from space. You will notice that 24 years later, in 2003, the summertime ice extent observed over the Arctic is less.

Now, while these images are very informative, with extensive coverage, we don't need space platforms to tell us that ice is disappearing. People sailing in the Arctic are now finding open water where they couldn't find it before in the summertime. Of course, in winter, ice cover becomes extensive each year. But the summertime decrease in sea ice in the Arctic is enormous, and this change is happening very rapidly. Future decreases may involve amplifying feedbacks, positive feedbacks that will melt the ice even faster. There are now some predictions that summertime Arctic sea ice could disappear by the end of this century (Northern Hemisphere sea-ice simulations by global climate models (Walsh and Timlin, 2003)).

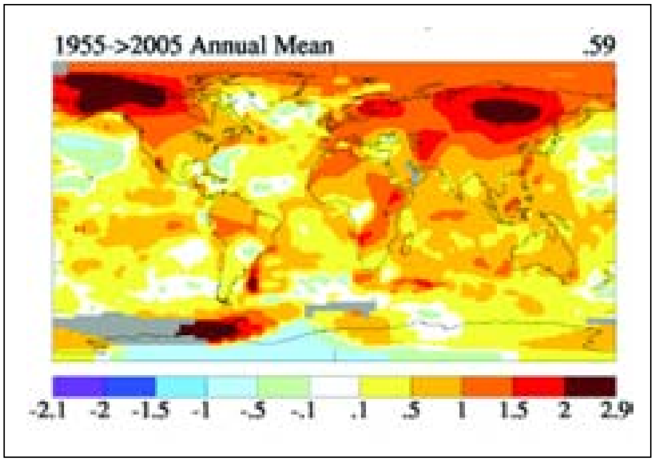


Figure 7. Annual and seasonal temperature changes observed over the past 50 years, from Hansen et. al. (http://data.giss.nasa.gov/gistemp/2005/).

There is another kind of indication of climate change which is less direct, but very dramatic. Two papers published in 2005 showed a statistically strong correlation between the warming since 1980 and the incidence of very strong hurricanes. Figure 9 defines a quantity called the power dissipation index (PDI). It is basically the cube of the speed of the winds rotating inside the storm, integrated over each storm's geographical extent and over time.

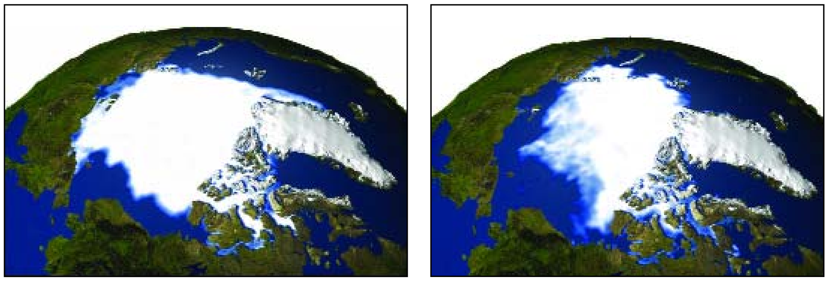
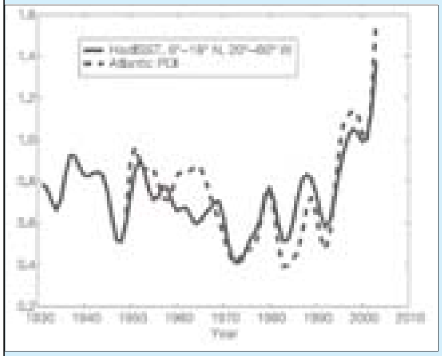


Figure 8. Images of Arctic sea ice in 1979 and in 2003, composite images from remote sensing data from satellite instruments (Comiso et al. 2003); Image credit: Scientific Visualization Studio, NASA Space Flight Center.

Power integrated over time is energy. So PDI is the total energy dissipated in a storm's lifetime. There has been a warming of the sea surface over the last 25 or 30 years; in fact, 40 to 50 years. And that warming has been accompanied by the increased incidence of strong storms. The statistics that hurricanes are more powerful are very clear. In fact, according to Emanuel, there has been something like a 60 percent increase in the incidence of the big category storms in the Atlantic and Pacific Ocean basins in the last 30 years. This graph was created before the enormous hurricanes and the 27 tropical storms of the year 2005, so the correlation will look even stronger when this graph is updated. The statistics about whether there are more hurricanes is not so clear.

Hurricane power dissipation index (PDI)



$$\mathrm{PDI} = \int_0^T V^3_{\max}\, dt$$

PDI has increased dramatically in recent decades in both the Atlantic and Pacific Ocean basins

Figure 9. The dashed curve is a measure of the power dissipated annually by tropical cyclones in the North Atlantic (the power dissipation index, PDI), while the solid curve is sea-surface temperature versus time (from Emanuel, 2005). Data have been smoothed and scaled as described by Emanuel; Atlantic hurricane power dissipation has more than doubled in approximately 30 years.

Part of the mechanism is understood. It has to do with warmer surface waters evaporating faster, and the latent heat of condensation from the extra water vapor in the atmosphere then becomes a source of extra energy for storms. But atmospheric conditions must also be conducive, and not all of the data needed to understand this pattern, either statistically or storm by storm, are available. Experts in the field have come to believe that the warming of the sea surface is contributing to the increased frequency of stronger storms (Emanuel, 2005; Curry et al., 2005).

GREENHOUSE GASES

The greenhouse effect, a natural phenomenon, has operated throughout Earth's history because of the physical properties of certain gases in the air, especially water vapor and carbon dioxide, and there is strong evidence that Earth would be much colder without the greenhouse effect. As humans change the chemical composition of the atmosphere, they also alter the size of the greenhouse effect; increases of the amounts of greenhouse gases were especially clear during the last half of the 20th century.

Figure 10 is regarded as a classic graph of data. It is from C. David Keeling and T. P. Whorf. This extensive graph displays their measurements of carbon dioxide from late 1957 through to the year 2005, taken at a very remote place, Mauna Loa, Hawaii, nearly every hour of every day for 47 years. The dots are the monthly averages of the data. You can see the over-all increase from 314 parts per million of air to 380 parts per million over this period, along with regular yearly cycles.

The cyclic behavior of the carbon dioxide is similar to the breathing of the planet, if you will. In the wintertime in the northern hemisphere, carbon dioxide is released into the atmosphere by the decaying of vegetation in the previous growing season and by the respiration of soils. Then, in the spring and summer of the following year, the carbon dioxide is drawn down by photosynthesis. So we see these beautiful annual cycles. The cycles enable quantitative study of the carbon cycle.

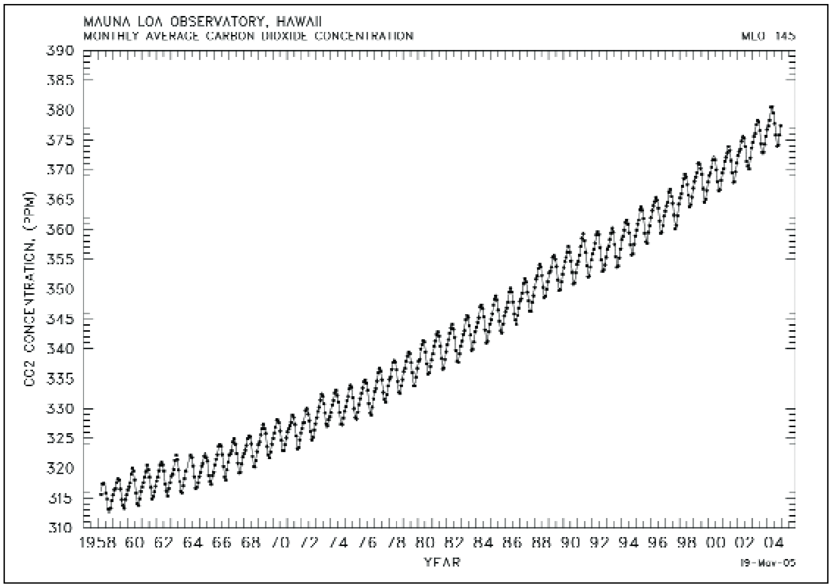


Figure 10. ***Monthly averages of carbon dioxide concentrations in air sampled at Mauna Loa, Hawaii measured by Professor C. D. Keeling from 1957 through 2004. Graph is available at http://cdiac.ornl.gov/trends/co2/graphics/mlo145e_thrudc04.pdf.***

But the more direct importance of this graph is the large and rapid increase in atmospheric carbon dioxide; many measurements elsewhere verify that the increase has been global, as must be the case for a long-lived gas whose mixing occurs much faster than processes that remove it from air. Carbon dioxide is an effective greenhouse gas, its amounts have increased and we have a very solid theoretical understanding for why climate change, notably a surface warming, should be occurring right now.

The observed increase of CO_2 worldwide can be compared to what is known about CO_2 amounts through geological history. Teams of scientists have obtained and analyzed dated ice cores from Greenland and Antarctica. Some of the dated ice cores have been pulled from two miles deep in particular parts of the Antarctic ice sheets. Figure 11 shows some of these data. During four ice ages in the past 450,000 years, CO_2 concentrations (blue curve) were approximately 180 ppm, and in the five warmer periods around the four ice ages, CO_2 concentrations rose to perhaps 280 to 300 ppm. The modern data are shown at the extreme right of Figure 11; current concentrations of 380 ppm are unprecedented historically in the sense that they had not appeared at any other time over the previous 450,000 years, during which time Earth had undergone several large climate changes. This set of data has now been extended back to 700,000 years, and the same conclusions hold.

The top graph in Figure 11 is a portion of the Keeling curve from the previous Mauna Loa figure with the red curve being the South Pole where the seasonal cycles are not so clear (little photosynthesis and biological respiration and decay occur there).

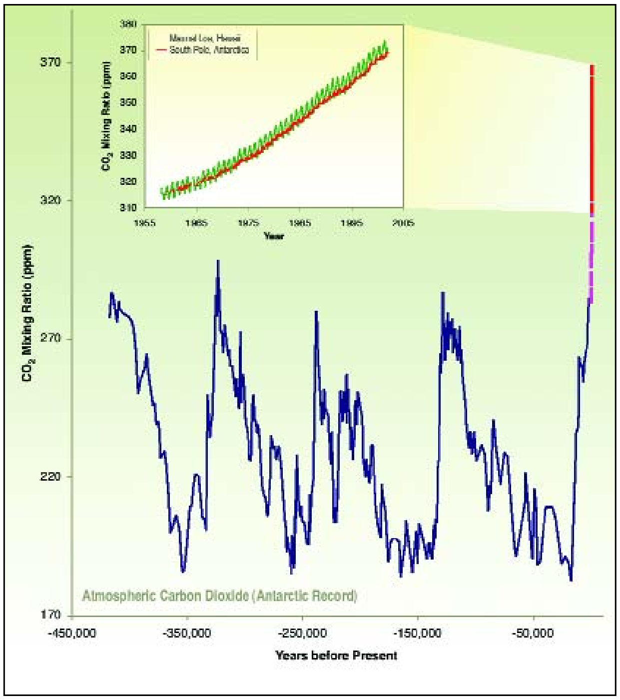


Figure 11. Summary of measured values of atmospheric carbon dioxide extracted from dated Antarctic ice cores (Petit et al., 1999) and (inset) from Mauna Loa and South Pole air samples (from Keeling and Whorf, 2005 and earlier Keeling and Whorf CDIAC data sets).

So the planet, in its natural cycles through Ice Ages and the interglacial warm times saw CO_2 amounts between 180 to 280 or 300 parts per million. Now if you hit "fast forward" to the modern times on the top graph, you will see that we have broken out of those natural ranges and the amounts observed are now approaching 385 parts per million in 2005-2006.

There are several kinds of evidence that this extra carbon dioxide is human-produced, through our use of fossil-fuel combustion: isotope evidence, and the geographical patterns of atmospheric CO_2, for example. There is no question in anybody's mind that I know that the modern carbon dioxide amounts are caused by fossil-fuel burning and by some land-use changes (perhaps a 15 to 20 percent effect).

How large are carbon dioxide emissions from human fossil-fuel energy consumption? Figure 12 shows that total global CO_2 emissions from burning of coal, oil, natural gas, gasoline, and wood have grown from a few hundred million metric tons of carbon in the form of carbon dioxide 100 years ago to 7 billion metric tons today, or more than one ton per person on Earth. Americans average about six tons of carbon each per year. Amounts emitted prior to 1880 or so are too small to be read from this graph.

Separately colored lines show the individual contributions from the burning of liquid fossil fuels, like oil and gasoline derived from it, from solids, like coal, and from the burning and the flaring of natural gas. Cement production, which also releases carbon dioxide, is also shown. The annual increase in measured CO_2 amounts in air is approximately 60 percent of the amount that is added annually from these sources. It is estimated that the remainder is absorbed into oceans.

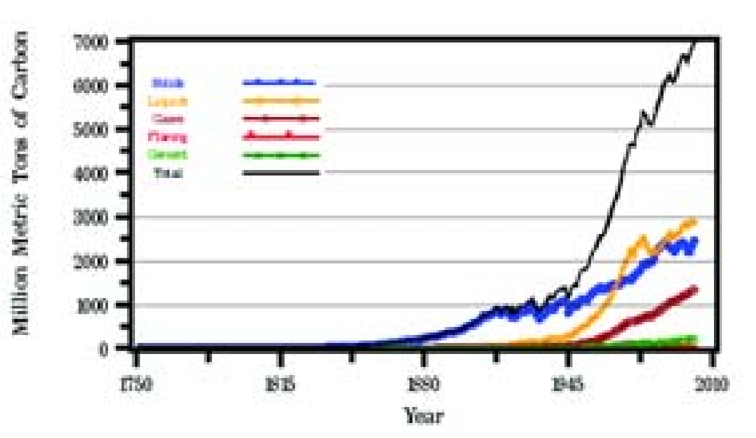


Figure 12. Estimated worldwide emissions of annual carbon dioxide due to burning of various carbon-based fuels and from cement manufacture for the period 1750-2002 A.D., from Carbon Dioxide Data Information Center (http://cdiac.ornl.gov/trends/emis/glo.htm).

The second-most important greenhouse gas that is growing due to humans is methane. Figure 13 represents the sources of atmospheric methane. The yellow part of the pie chart is the portion of methane released to the atmosphere every year that we think is natural. The red part is due to human activities, and it's about twice as big. From direct measurements and from recent ice cores, we know that atmospheric methane has doubled in concentration in the last 100 years, so this ratio of human-driven to natural sources is plausible. The annual total source, 540 million metric tons, is known to within 15 or 20 percent, as is the amount from enteric fermentation (cows). Other individual entries in this figure are not known as precisely. A new report has proposed that there may be another natural source of methane from the exudations of various plants which had not been recognized previously, but various measurements must be replicated before being accepted.

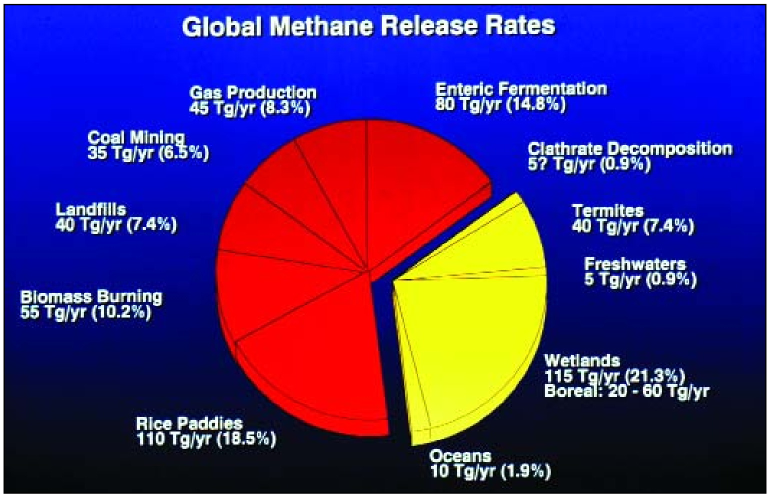


Figure 13

The important points are that atmospheric methane has increased by more than a factor of two since the late 19th century, and data from the last few ice ages show that we now have amounts of methane in the global atmosphere that are five times as much as during the glacial periods of the last 700,000 years, and that human-driven sources are the cause.

We are probably seeing the impact of the greenhouse gases on our climate now. Please refer back to Figure 3. As noted, there are very interesting features here, the warming from 1900 to 1940 and the cooling from 1940 to 1975. But the dominant feature is this monotonic and rapid rise of the last 25 to 30 years, and I want to reemphasize the importance of this period.

Let me introduce a few more numbers. The impact on the Earth's energy budget due to the increases in greenhouse gases over the last 100 years is about 2.6 watts per square meter (NRC, 2005). Carbon dioxide alone has caused an additional 1.6 watts per square meter of extra power (energy per unit time) to be trapped in the Earth's lower atmosphere regions. Methane (CH_4) is the second most important of the anthropogenic gases (see Figure 14).

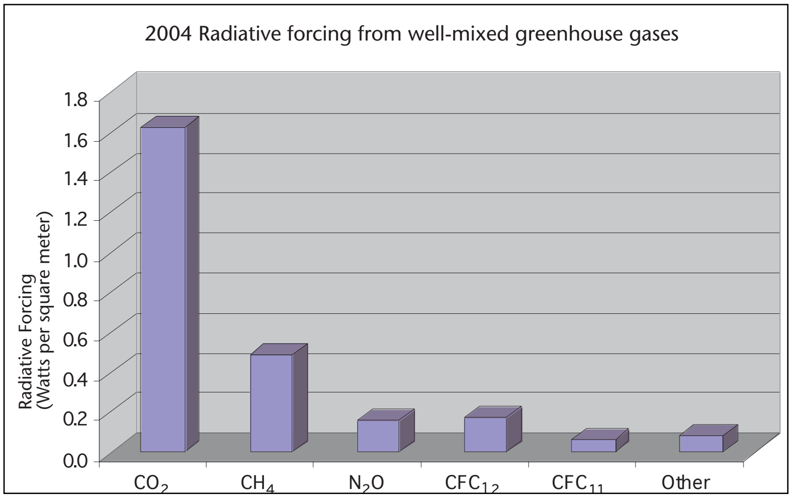


Figure 14. ***Radiative forcing (warming) effect of the increased concentration of several greenhouse gases. Concentration increases, roughly those of the past 100 years, are taken from http://www.cmdl.noaa.gov/climate.html. Radiative forcing (energy trapped per unit time and area in lower atmosphere) is computed by formulas given in IPCC (2001). See also NRC (2005).***

If the growth of the fluorocarbon industry had continued at the rates of the 1960s and 1970s, it would have resulted in the combined histograms for the CFC's in Figure 14 being taller than the carbon dioxide block. In fact, had it not been for the Montreal Protocol, for which we have to thank Ambassador Benedick and some other people, and the creation of substitute chemicals for two refrigerants (CFC-12 and CFC-11), CFC's would have surpassed CO_2 as greenhouse gases by 1990 (Hansen et. al. 1990).

So total radiative forcing, that is the impact on the Earth's surface energy budget due to these greenhouse gases now, is about 2.6 watts per square meter. Now let us compare that with what might be happening due to the sun. The last 25 or 30 years is different for another reason. It is the first time in human history that scientists have measured the output of the sun with enough precision to be able to answer the question of whether the sun's output is changing; for example, increasing enough to warm the planet.

Figure 15 shows solar irradiance data measured between 1979 and 2005. The authors merged the best data possible from different satellite instruments that have been flying since 1978 or 1979 to obtain a record of the observed change in the sun's output over that period. You will see that it is roughly repeatable, with solar cycles like sine waves with eleven-year periods. We knew about 11 year solar cycles, but what we didn't know how the total output of the sun varies every 11 years. The answer is 0.1 percent. When you go through the geometry, that's equivalent to an oscillation of 0.2 watts per square meter at the surface of the Earth. The greenhouse gases add 2.6 watts per square meter, and the greenhouse effect continues. It is sustained and it grows. It does not go up and down like a sine wave (as does the sun's output).

If someone wants to postulate that the warming of the last 25 years is due to the sun's activity, they have a hard time doing it now that these data are available. It is an untenable argument. Theoretically, if the small changes in the sun's output are causing some climate and weather changes, then we really have to be worried about the greenhouse effect, because it is much larger, it is sustained, and it is growing, so its eventual consequences will be similarly larger.

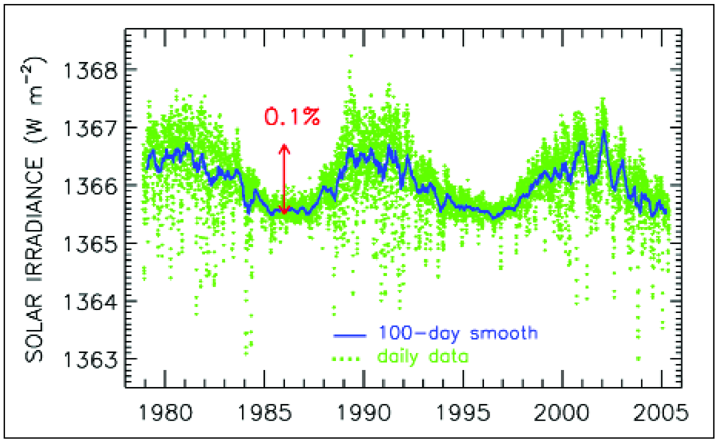


Figure 15. Solar irradiance data from Frohlich and Lean (2004) with updates from Frohlich taken from http://www.pmodwrc.ch/. No long-term trend is observed.

ENERGY EFFICIENCY

The theme of this year's NCSE Symposium is energy. As Mr. Train mentioned earlier, we have a polarized situation and many disagreements are going on, especially in the political realm. There remain some things that we can agree on, though. I propose that energy efficiency must be one of them.

What does energy efficiency accomplish for us? Figure 16 lists seven benefits. First of all, from a United States point of view, decreasing our dependence on foreign oil has multiple benefits and you can fill in the ones that you put most stock in yourselves, for example, decreased oil imports would certainly improve national security. We would be in a stronger negotiating position; we wouldn't have to deploy our military in the case of oil shortages. We import about 12 million barrels of oil per day, and a typical oil tanker holds about 800,000 barrels, so there are roughly 15 oil tankers a day arriving in the United States fully loaded. They are all sitting ducks on the ocean.

Increasing energy efficiency would also decrease our trade deficit. If you multiply 12 million barrels a day times 365 days a year by $50 a barrel, you calculate a number of over $200 billion as a "contribution" to our annual trade deficit. One might also ask what fraction of this sum of money goes into the hands of other-than-legitimate interests.

Immediate action with multiple benefits.
Energy efficiency would:

- **Decrease our dependency on foreign oil.**
- **Improve our national security.**
- **Decrease our trade deficit.**
- **Decrease local air pollution.**
- **Increase our national competitiveness.**
- **Encourage development of new products for global markets.**
- **Decrease household energy costs while also slowing the increases of CO_2 and CH_4.**

Figure 16

We could also decrease local air pollution by improving energy efficiency and decreasing fossil fuel combustion. Further, we could also increase national competitiveness. For example, the cost of manufactured goods includes the cost of energy. In times of low energy prices, people don't pay much attention. But when energy prices go up, this becomes a significant part of the cost of manufactured goods. Comparing ourselves to Japan and Germany —- their energy efficiency in manufacturing is probably 40 percent better than ours.

By committing to a goal of improved energy efficiency, we could encourage development of new products for global markets, which everyone wants to buy — energy-efficient products. People want to enjoy the benefits of lower energy costs. There is a growing global demand for energy-efficient products and devices. If we fail to develop new energy-efficient products, we will forfeit this growing global market. Another benefit of energy efficiency would be to decrease household energy costs.

Finally, improved energy efficiency would reduce the emissions of carbon dioxide and of methane (which comes partly from the handling and use of fossil fuels — after all, methane is natural gas). With all of these benefits, increased energy efficiency should be a common goal for all of us. There must be ways to get more people to agree that there is some benefit for them to work on energy efficiency.

BEING USEFUL THROUGH SCIENCE

As important as it is to have detected contemporary climate change and to develop a theoretical understanding of why it is changing, there is a great deal more that scientists can do to be useful to society. I want to illustrate some of the potential for value, and also express some concern that we not waste that potential. Figure 17 lists a few points, the first of which is that our highly polarized discussion is obscuring our priorities.

Being Useful Through Science

Polarized discussion obscures priorities.

We must accelerate scientific research to deliver more useful results.

For example,

- **Regional precipitation and hydrology.**
- **Extreme events like daily high temperatures to be expected and minimum nightly temperatures in summer.**
- **Arctic sea-ice futures.**
- **What to expect after the next stratosphere-penetrating volcano?**

Figure 17

For example, when environmental groups and anyone who is trying to forward an environmental agenda says that “the science is settled, let’s get on with the action,” he/she is selling future science short. How often have you heard that phrase that “the science is settled?” I don’t like it. While climate change has been detected and the evidence of human-caused climate change is very strong, maybe one question is settled, but there are many more questions that demand answers, and we have a lot more to do.

To say that science is settled is telling people that the scientific challenge is over, that it is not useful anymore, which is an irrational approach to the future. On the other hand, people who say that the science is confused and there is not enough evidence to take any action, are not being at all helpful, even if they are trying to be truthful — which is not always clear.

What are the things that we need to do? We have to dedicate more emphasis toward understanding regional precipitation and hydrology. How is it changing, how will it change? Water needs are so important in regions where people live, where animals live, where natural biota have adapted to regional climates and to regional precipitation patterns and rivers.

We can do a better job of predicting. For example, we must become able to predict the snow pack that accumulates over a winter and how it is going to be changing and what the spring runoff is going to be. These goals are not impossible, but they need much sustained research.

Climate is also very importantly measured by extreme events, not just by average temperatures. In fact, the direct effects of average temperatures don't worry us very much. Instead, it is critical to know how the daily high temperatures will change. What can be expected? And what's happening, and what will happen to the minimum nightly temperatures? Minimum nightly temperatures in the summer drive our demand for water and for air conditioning, and in stressed animals or people, also add more danger. As to electrical power plants, peak power demands determine what generation capacity is needed, while many parameters for electrical transmission networks depend also on minimum nightly temperatures in the summertime. By the way, there is evidence that the daily temperature range is changing. Nighttime temperatures are rising faster than the daytime temperatures are, and this is a signature of the greenhouse effect. While they are both going up, the nighttime temperatures are rising faster.

Being Useful Through Science - II

- Effectiveness of policies to retard radiative forcing by slowing the CO_2 increase, slowing the N_2O increase, reducing atmospheric CH_4 and tropospheric O_3, reducing emissions of extremely long-lived gases.
- Statistics of storm-driven sea surges for infrastructure and emergency planning and the insurance industry, statistics of hurricane intensities and frequencies.
- Improved predictions of hurricane tracks (sea temperatures (depth), wind measurements by A/C and remote sensing, ships).
- Communications: Climate is more than surface temperatures.
- What is known and not known…

Figure 18

Arctic sea ice futures demand attention. We have issues of ecology and life in the Arctic, for the organisms that live there, as well as for commercial and strategic issues surrounding the Arctic sea ice. We have great need to be able to predict and understand what's been happening, and progress is feasible if we stay with the task.

And for several reasons, we should research what to expect after the next stratosphere-penetrating volcano, the kind of which Richard Benedick reminded us. It will cool the planet. The last time this happened, in June of 1991, several climate modelers successfully predicted how much the planet would cool, and they predicted the time course of the cooling. Supporting a strong general research program now, we can be ready as soon as the next such volcano goes off to predict how much it should cool and where, and when the cooling will cease and become a warming again.

Continued resolve to research the climate system will enable us to deliver a number of other useful results such as those exemplified in Figure 18. Certainly we must help policy makers, business leaders, and the general public to figure out the effectiveness of policies to slow down this radiative forcing, by slowing down the carbon dioxide increase and those of the other greenhouse gases, like nitrous oxide and methane. It is a legitimate and necessary role for scientists to work through those calculations and projections objectively and carefully for everyone who has to make individual choices and governmentally based and commercially based decisions.

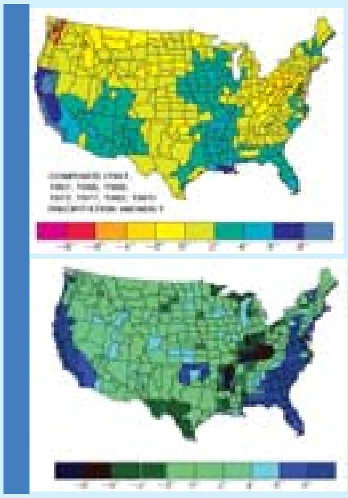
We can do a much better job on the statistics of storm-driven sea surges. As sea level rises, sea surges, especially in the presence of severe storms and stronger severe storms, are going to grow. And unfortunately, we keep building more facilities, residences, and installations along coastal domains. Even though we will probably not be able to predict individual storms for the foreseeable future, we can do a much better job on the statistics of these storm events and the sea surges that will come from them, as well as the statistics of hurricane intensities. And I would not be surprised if the hurricane frequencies are there to be predicted, even though trends have not been detected yet because the data are so noisy.

Also, if we get serious about measuring not only the sea temperatures at the surface, but as a function of depth, and by getting better air humidity and wind measurements in individual storms, we should be able to do better predictions of whether or not a specific hurricane is going to make landfall, and where it will dissipate, to gain capability to anticipate and prepare for storms such as those that caused the dramatic tragedies that the Gulf Coast had in 2005. But it is going to take a commitment similar to the kind that Mr. Train mentioned along all environmental lines. It will require a commitment of our government, as well as other people.

Communicating with the general public is ever more important. All of us have much to learn and to discuss about what climate is, and what it means to us. Chris Bernabo made an excellent start on this topic 15 or 20 years ago and showed that those of us on the research side were not doing a very good job of listening and/or communicating with the general public and learning what they need to know about climate change, both to gain support for our research and for making it more useful. And of course, we must always communicate what is known and what is not known.

I want to give an example from 1997-1998, from a field that I did not pay much attention to, research on understanding and predicting El Nino events, historically natural events. The upper graph of Figure 19 shows what was predicted in the fall of 1997 in the form of rainfall six to eight months later, in January through May, based on looking at the patterns that were being observed in the eastern tropical Pacific. The 1997 waters were much warmer in the eastern tropical Pacific than normal, and based on the previous eight El Nino southern oscillation events (ENSO), scientists predicted that California would be much wetter than normal in the winter to come.

1997-98 El Nino Precipitation Anomalies



Predicted precipitation anomalies for Jan-May 1998 based on composite of eight previous ENSO events

Actual precipitation anomalies (relative to long-term averages) for Jan-May 1998

*Figure 19. **Seasonal precipitation anomalies from National Ocean and Atmospheric Administration (NOAA) Climate Prediction Center (see also Monteverdi and Null, 1997).***

The upper graph is predicted anomalies in January through May precipitation, based on eight El Nino events prior to 1997, and the lower graph is what actually happened at corresponding times and places in 1998. As you look at the upper graph on the left, you will see California in blue and violet, indicating predictions for five or more inches of extra winter rain over the coming few months due to this El Nino. The bottom graph shows what actually happened, using the same color code.

For California, these predictions were very good and valuable. For example, on December 7, 1997, in Laguna Beach, there were almost seven inches of rain in six hours in an area that is usually pretty dry. People who had access to, and heeded this prediction three months earlier, who cleaned out their storm drains, cleaned out the brush in ravines, fixed their roofs, repaired leaks on their houses and commercial properties, did very well by themselves. They saved money and they were safer from this very useful prediction.

This is one of the kinds of information that we are going to have to learn to deal with. What is possible for the scientific community to predict may not be exactly what people want. For example, the people of Laguna Beach would have liked to know that there was going to be seven inches of rain in six hours on December 7, 1997. Or that it was going to rain in San

Francisco on a particular day, or something similar. That specificity was not in the cards, but still, the coarser prediction was very useful.

There were also some differences between predictions and actual precipitation. For example, the East Coast turned out to be much wetter, Florida and up, than was predicted.

But the prediction, as it was, was still extremely valuable, and as I recall the California patterns were predicted with higher odds than were those for the East Coast.

So we must work together with the general public and the scientific community to understand what can be predicted, what would be useful, and get on with it. Climate change is underway and it will continue, especially because we are not doing very well in slowing down carbon dioxide and our consumption of fossil fuels. Change will probably accelerate, with possible manifestations in severe storms and other extreme events. While we continue to try to suppress human forcing of climate change, we must also gain ability to predict and to make those predictions as useful as possible to the public at large.

It has been an honor to be here with you, in honor of Senator John Chafee. I hope that I have contributed useful thoughts to the day's proceedings. Thank you for the opportunity.

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Appendix I

Biography of Senator John H. Chafee

Senator John H. Chafee (R-RI) was born in Providence, Rhode Island, in 1922. He earned degrees from Yale University and Harvard Law School. Upon the United States' entry into World War II, Chafee left Yale to enlist in the Marine Corps, and then served in the original invasion forces at Guadalcanal. In 1951 he was recalled to active duty and commanded a rifle company in Korea.

Chafee began his political career by serving for six years in the Rhode Island House of Representatives, during which time he was elected Minority Leader. He was then elected Governor by a 398-vote margin in 1962. He was reelected in 1964 and 1966 — both times by the largest margins in the state's history. In January 1969 he was appointed Secretary of the Navy and served in that post for three-and-a-half years. He was elected to the United States Senate in 1976.

As Chairman of the Environment and Public Works Committee, the Senator was a leading voice in crafting the Clean Air Act of 1990. He led successful efforts to enact oil spill prevention and response legislation and a bill to strengthen the Safe Drinking Water Act. Senator Chafee was a long-time advocate for wetlands conservation and open space preservation and was the recipient of every major environmental award.

As senior member of the Finance Committee, Senator Chafee worked successfully to expand health care coverage for women and children and to improve community services for people with disabilities. In 1990, Senator Chafee spearheaded the Republican Health Care Task Force. He went on to lead the bipartisan effort to craft a comprehensive health care reform proposal in 1994.

Senator Chafee also was a leader in efforts to reduce the federal budget deficit and co-chaired the centrist coalition that produced a bipartisan balanced budget plan in 1996. He was an active proponent of free trade and was a strong supporter of the North American Free Trade Agreement (NAFTA). He served as Chairman of the Republican Conference for six years.

The Senator received awards and endorsements from such organizations as the National Federation of Independent Business, the American Nurses Association, the League of Conservation Voters, the Sierra Club, Handgun Control Inc., Planned Parenthood, Citizens Against Government Waste, and the National PTA.

On October 24, 1999, Senator John H. Chafee died from congestive heart failure. He is sorely missed.

Appendix II

Biography of Dr. Ralph J. Cicerone

Ralph J. Cicerone, president of the National Academy of Sciences, is an atmospheric scientist whose research in atmospheric chemistry and climate change has involved him in shaping science and environmental policy at the highest levels nationally and internationally.

Dr. Cicerone's research has been recognized through several honors and awards. His research was recognized on the citation for the 1995 Nobel Prize in Chemistry awarded to University of California, Irvine, colleague Sherwood Rowland. The Franklin Institute recognized his fundamental contributions to the understanding of greenhouse gases and ozone depletion by selecting him as the 1999 laureate for the Bower Award and Prize for Achievement in Science, one of the most prestigious American awards in science. In 2001, he led a National Academy of Sciences study of the current state of climate change and its impact on the environment and human health at the request of President Bush. In 2002, he was awarded the Roger Revelle Medal by the American Geophysical Union. In 2004, the World Cultural Council honored him with another of the scientific community's most distinguished awards, the Albert Einstein World Award in Science.

Early in his career, Dr. Cicerone held faculty positions in electrical and computer engineering at the University of Michigan. In 1978 he joined the Scripps Institution of Oceanography at the University of California, San Diego, as a research chemist. From 1980 to 1989, he served as senior scientist and director of the atmospheric chemistry division at the National Center for Atmospheric Research in Boulder, Colorado. In 1989 he was appointed the Daniel G. Aldrich Professor of Earth System Science at the University of California, Irvine, and chaired the department of earth system science from 1989 to 1994. Dr. Cicerone served as the dean of physical sciences for the next four years at University of California, Irvine, then as chancellor of the University from 1998 to 2005.

Dr. Cicerone is a member of the National Academy of Sciences, the American Academy of Arts and Sciences, and the American Philosophical Society. He has served as President of the American Geophysical Union, the world's largest society of earth scientists, and received its James B. Macelwane Award in 1979 for outstanding contributions to geophysics. He has published hundreds of refereed and conference papers and has presented invited testimony to the U.S. Senate and House of Representatives on a number of occasions.

Dr. Cicerone received his bachelor's degree in electrical engineering from the Massachusetts Institute of Technology where he was a varsity baseball player. He then received master's and doctoral degrees in electrical engineering from the University of Illinois, Urbana.

Appendix III

LIST OF JOHN H. CHAFEE MEMORIAL LECTURES ON SCIENCE AND THE ENVIRONMENT

2000

Sherwood Rowland, Nobel Laureate, University of California Irvine
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