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CLIMATE CHANGE 2001: A CRITIQUE

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This critique builds on *A Global Warming Primer* available on-line as a pdf file at http://www.nationalcenter.org/NPA420. Like the *Primer*, its purpose is to help the reader determine whether our understanding of the earth's climate is adequate to predict the long-term effects of carbon dioxide emissions from the continued burning of fossil fuels, to permit informed public policy decisions. This is a limited critique, looking only at a few topics covered in the latest report of the Intergovernmental Panel on Climate Change (IPCC). That report is far more thorough and comprehensive than the earlier ones. It is available on-line at http://www.grida.no/climate/ipcc_tar/wg1/index.htm.

Entitled *Climate Change 2001: The Scientific Basis*, *the Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, the volume is remarkable for many reasons, not least of which is that it has essentially eliminated the Medieval Warm Period of the 11th to 14th centuries and the Little Ice age of the 17th to 19th centuries. The report states categorically that "current evidence does not support globally synchronous periods of anomalous cold or warmth over this time frame, and the conventional terms of 'Little Ice Age' and 'Medieval Warm Period' appear to have limited utility in describing trends in hemispheric or global mean temperature changes in past centuries… The long-term trend is best described as a modest and irregular cooling from AD 1000 to around 1850 to 1900, followed by an abrupt 20th century warming." The elimination of The Medieval Warm Period and the

Little Ice Age is dramatically shown by comparing Fig. 1 with Fig. 2 [adapted and augmented by the IPCC from Mann, et al. (1999)].

The way Fig. 2 is presented forces the interpretation, upon even the most casual reader, that natural variations until the twentieth century are relatively small, and the dramatic rise at the beginning of the twentieth century is certainly abnormal, supporting the IPCC claim that this exceptional rise in temperature is due to human activities. But if this is indeed the case, one might ask why the temperature begins to rise so dramatically at the beginning of the Industrial Revolution before the emission of substantial amounts of carbon dioxide.

Both figures 1 and 2 are from IPCC reports. They are clearly inconsistent. Figure 1 purports to show *global* temperature change during the Medieval Warm Period and Little Ice Age, while Fig. 2 shows the variations of the average surface temperature of only the Northern Hemisphere. One would expect Fig. 2 to show a greater variation than Fig. 1. After all, it is the Northern Hemisphere that the IPCC claims showed the greatest temperature variation during the Medieval Warm Period and Little Ice Age. But even if the effects of these periods were geographically restricted as claimed by the IPCC, is the averaging procedure used a reasonable approach to assessing the reality and past effects of the Medieval Warm Period and Little Ice age? And most importantly, were the temperature variations of these periods geographically restricted to the limited region claimed by the IPCC?

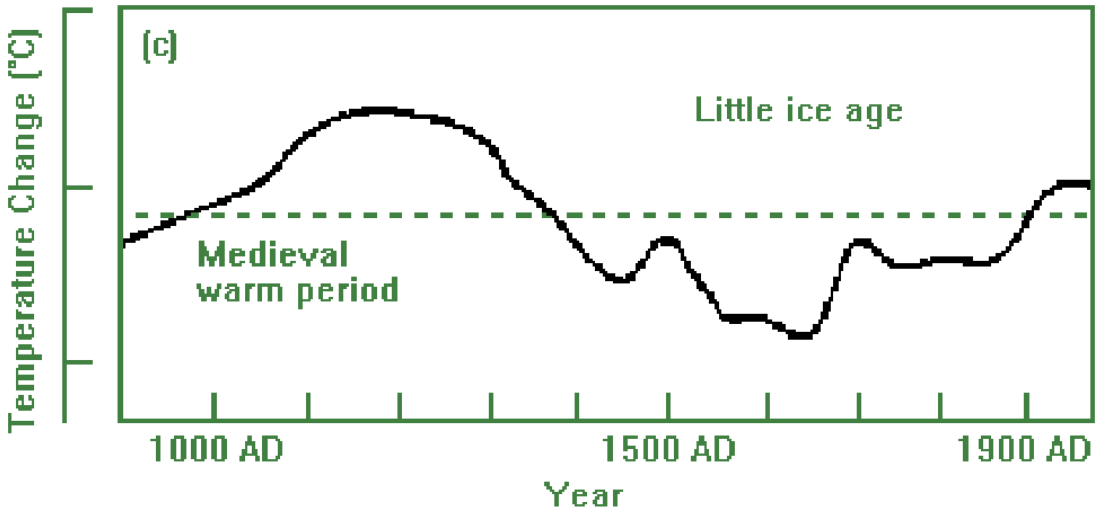

Figure 1. Global average temperature change during the Medieval Warm Period and Little Ice Age. Each division of the temperature change scale corresponds to 1 °C. [Adapted from Fig. 7.1 of *Climate Change: The IPCC Scientific Assessment* (Cambridge University Press , Cambridge 1991)]

Even if the effects of the Medieval Warm Period and Little Ice age were geographically limited, I would argue that the answer to the first question is a resounding, No! If the thermohaline circulation in the Atlantic were to change dramatically as a result of climate change, with Europe consequentially thrown into a new ice age [Clark, et al. (2002)], one would not dismiss the change as inconsequential because the average temperature of the entire northern hemisphere was not as dramatically affected as that in the north Atlantic and surrounding landmasses. Whatever the origin of the Medieval Warm Period and Little Ice Age, they were historical events with severe impacts on people of the period.

There is every reason to think that climate variation, natural or not, will lead to non-uniform geographical effects. Nonetheless, as discussed below, the Medieval Warm Period and Little Ice age were apparently global phenomena, Fig. 2 notwithstanding.

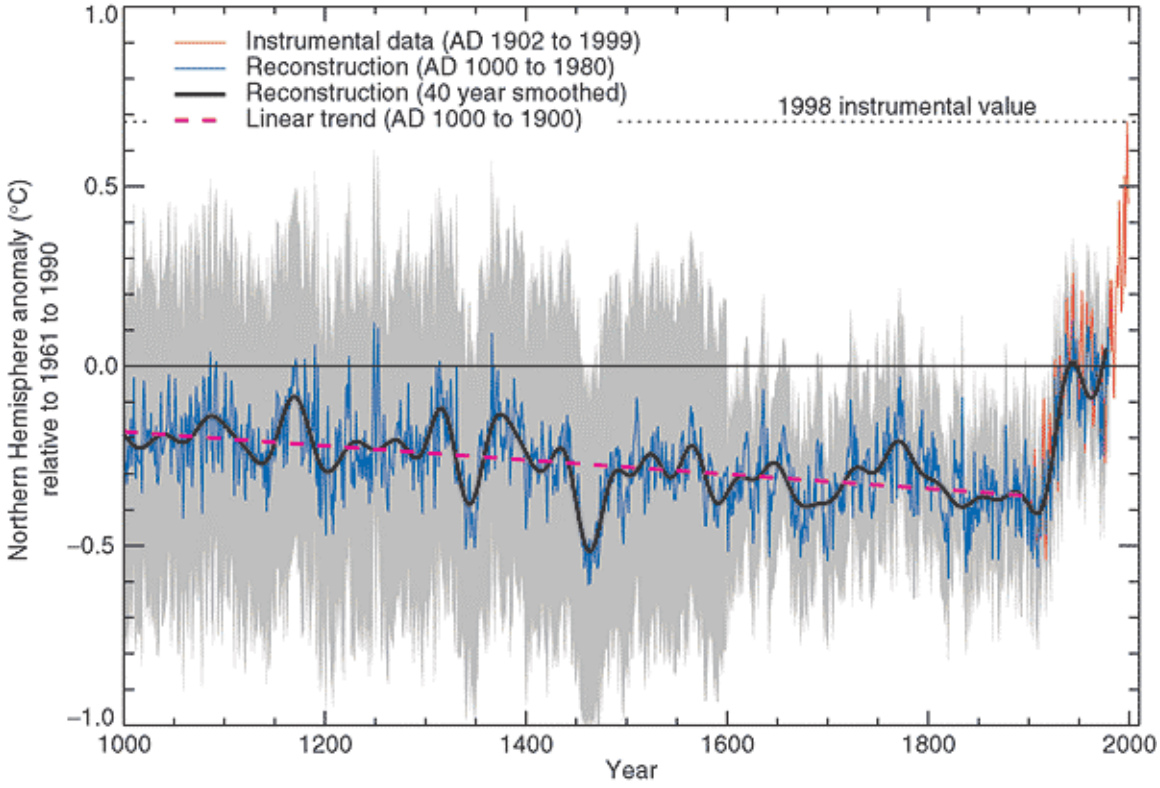

Figure 2: Millennial Northern Hemisphere (NH) temperature reconstruction (blue) and instrumental data (red) from AD 1000 to 1999, adapted from Mann et al. (1999). Smoother version of NH series (black), linear trend from AD 1000 to 1850 (purple-dashed) and two standard error limits (grey shaded) are shown. [Fig. 2.20 and caption from *Climate Change 2001: The Scientific Basis*]

Broecker (2001) has argued very persuasively that the warming after 1860 was natural and a result of the most recent in a series of similar warmings spaced at roughly 1500-year intervals throughout the present interglacial. Bond, et al. (1999) have shown that the climate has oscillated over the past 100,000 years, with a period close to 1500 years, and that the change from the Medieval Warm Period to the Little Ice age was the penultimate of these swings. In answer to the second question, Broecker concludes with great forcefulness that "The Little Ice Age and the subsequent warming were global in extent."

In fact, Mann et al., a principal source for Figure 2, while observing that "the 1990s are likely the warmest decade, and 1998 the warmest year, in at least a millennium," are careful to caveat that by stating that "More widespread high-resolution data which can resolve millennial-scale variability are needed before more confident conclusions can be reached with regard to the spatial and temporal details of climate change in the past millennium and beyond."

Mann et al. use in their version of Figure 2 the mean temperature of 1902-1980 as the calibration period. This allows them to make the point that "The late 11th, late 12th, and late 14th centuries rival *mean* 20th century temperature levels. Our [temperature] reconstruction thus supports the notion of relatively warm hemispheric conditions earlier in the millennium, while cooling following the 14th century could be viewed as the initial onset of the Little Ice Age." As adapted by the IPCC, Figure 2 exaggerates the negative value of the anomaly by using the period 1961-1990 as the calibration period. This has the effect of lowering the entire graph about 0.15 ^{o}C.

Whether the Medieval Warm Period and Little Ice age were global in extent or not, it is clear from the historical record and uncertainty in the science that presenting the temperature record as in Figure 2 is misleading at best. The IPCC *Summary for Policymakers* reproduces Figure 2 and states that, "Reconstructions of climate data for the past 1,000 years also indicate that this warming was unusual and is unlikely to be entirely natural in origin." The key word here is "unlikely." By the IPCC definition,

"unlikely" means that there is up to one chance in three that the warming *is* entirely natural in origin. The IPCC is far from categorical in asserting that people are the sole cause of the warming. The phraseology even leaves open the possibility that the fraction of the warming that is due to natural causes could be very large.

As clearly stated by Baliunas (2002), "Because about 80% of the carbon dioxide from human activities was added to the air after 1940, the early 20th century warming trend had to be largely natural. Human effects from increased concentrations of greenhouse gases amount to at most 0.1 ºC per decade—the maximum amount of the surface warming trend seen since the late 1970s."

The warming being discussed is surface warming. Warming of the lower troposphere (about 5000 to 28,000 feet in altitude), as measured by microwave sounder instruments onboard NASA satellites, is considerably smaller, showing a linear warming trend of only 0.04 ºC per decade since 1975. As shown in Baliunas' testimony, global tropospheric temperature since 1955 as measured by radiosonde instruments on balloons shows a warming trend of 0.09 ºC per decade if fitted across the *entire* period since 1955, but no evidence of a warming trend if compensated for the Pacific Decadal Oscillation [see Note 1]. This oscillation is not related to human causes. It occurs every twenty to thirty years, and in the period since 1955 happened abruptly in 1976-1977 when global tropospheric temperature increased by some 0.4 ºC.

These *measurements* contrast sharply with the climate model *simulations* upon which the IPCC's report is based. Model simulations show a warming of the lower troposphere that is not observed. In the IPCC's own words, "Natural climate variability and the influence of natural external forcing, such as volcanism, can explain part of this difference. However, a discrepancy remains that cannot be accounted for with current climate models."

Solar Forcing

The latest IPCC report is also remarkable with regard to its treatment of solar forcing of climate. Total solar irradiance in the past is difficult to determine and

may—for the period since the Maunder Minimum (associated with the Little Ice Age) of the mid-1600s to the early 1700s—have an uncertainty of anywhere from 1 to 15 watts per square meter (W/m^2). Of course, what really matters is not the absolute uncertainty but the relative uncertainty over the time period of interest. The data are shown in Figure 3 below.

The report chooses to use as a basis for determining the increase in solar radiative forcing since 1750 the difference between the TSI values at the (11-year) solar cycle minima in 1744 and 1996, as taken from Lean, et al. (the red curve) in Fig. 3. Using these dates leads to an increased radiative forcing of 0.3 W/m^2 (See Note 2). Readers may judge for themselves whether the choice of these dates makes sense. The report also gives the reasonable range for solar radiative forcing of 0.1 to 0.5 W/m^2, although the low end seems very unlikely (see the discussion in the *Global Warming Primer*).

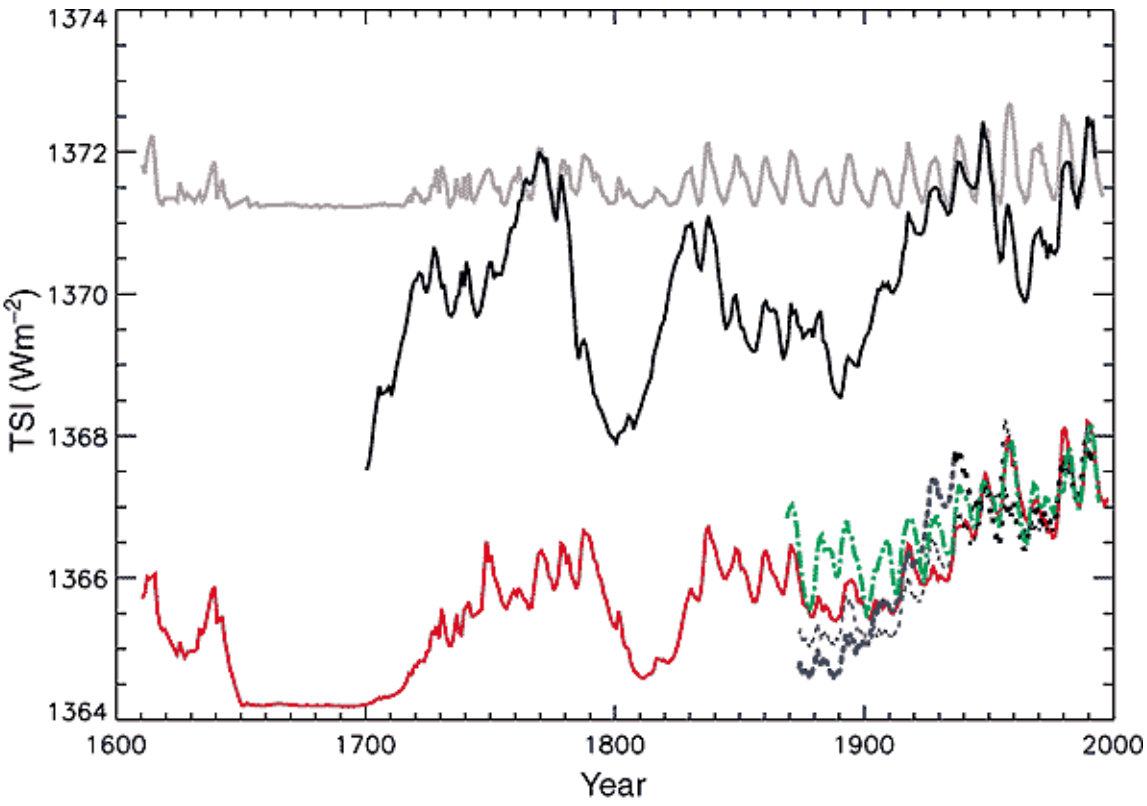

Figure 3: Reconstructions of total solar irradiance (TSI) by Lean et al. (1995, solid red curve), Hoyt and Schatten (1993, data updated by the authors to 1999, solid black curve), Solanki and Fligge (1998, dotted blue curves), and Lockwood and Stamper (1999, heavy dash-dot green curve); the grey curve shows group sunspot numbers (Hoyt and Schatten, 1998) scaled to Nimbus-7 observations for 1979 to 1993. [Fig. 6.5 and caption from *Climate Change 2001: The Scientific Basis*]

Bond et al. (2001) have shown that over the last 12,000 years every centennial time scale increase in drift ice in the north Atlantic was probably a result of reduced solar output. In particular, the last cycle was correlated with the Medieval Warm Period and the Little Ice Age. They concluded that "both may have been partly or entirely linked to changes in solar irradiance [and] it seems almost certain that the well-documented connection between the Maunder solar minimum and cold decades of the [Little Ice Age] could not have been a coincidence." Most importantly, the "Earth's climate system is highly sensitive to extremely weak perturbations in the Sun's energy output, not just on the decadal scales that have been investigated previously, but also on . . . centennial to millennial time scales." They also determined that the solar influence on climate was truly global, extending from polar to tropical latitudes.

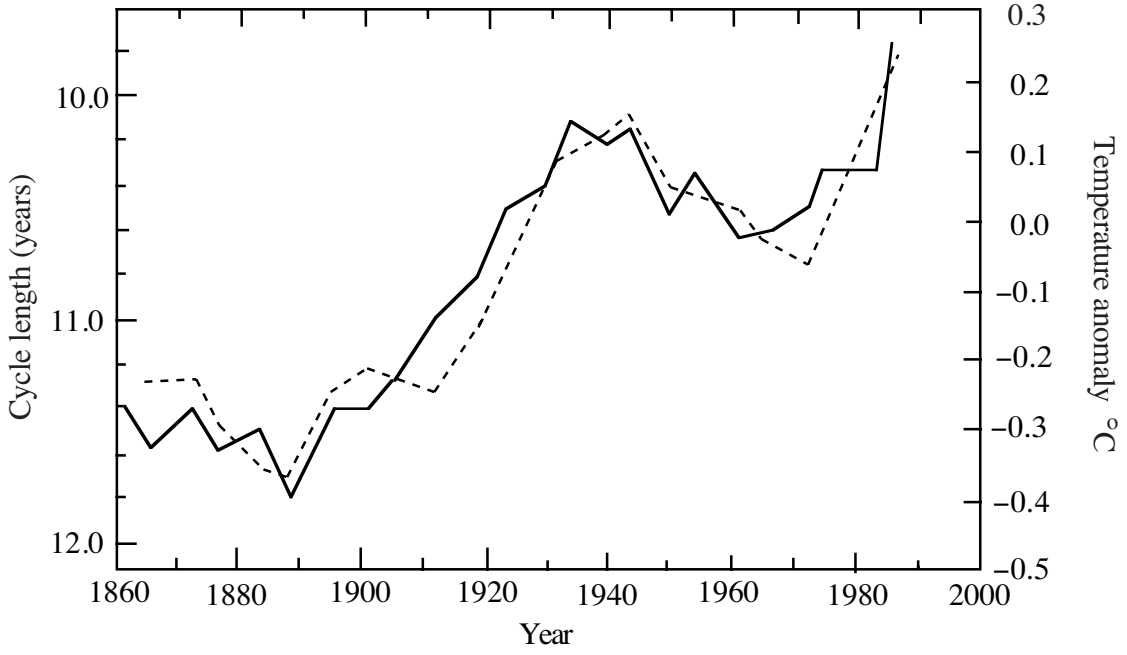

Figure 4. Solar cycle length (solid curve) and Northern Hemisphere temperature anomalies (dashed curve) as a function of year. The cycle length is plotted at the central time of the actual cycle. Note the inverse scale for solar cycle length: short solar cycles correspond to periods of high solar activity, and long cycles to reduced activity. [Adapted from E. Friis-Christensen and K. Lassen (1991)]

Their work is supported by that of Shindell, et al. (2001) who found that the global temperature dip during the Maunder Minimum was small, on the order of 0.3°C to 0.4°C, but that temperatures on the northern hemisphere continents were lower, especially

during winter, by 1°C to 2°C. They conclude by stating that "relatively small solar forcing may play a significant role in century-scale [Northern Hemisphere] winter climate change" and that "colder winter temperatures over the [Northern Hemisphere] continents during portions of the 15th through 17th centuries (sometimes called the Little Ice Age) and warmer temperatures during the 12th through 14th centuries (the putative Medieval Warm Period) may have been influenced by long-term solar variations."

The very strong correlation between temperature change and changes in solar activity can be seen from work now over ten years old. Instead of the usual smoothed sunspot number, Friis-Christensen and Lassen (1991) introduced solar cycle length as a new measure of solar activity, and compared the solar cycle length with observed temperature anomalies since 1860 relative to the period of 1951-1980. The result is shown in Fig. 4. The correlation is striking. Note also that the decrease from 1945 to 1970 is readily apparent. Friis-Christensen and Lassen conclude their paper with the strong caution that "Estimation of the natural variability of the Earth's climate and its causes are needed before any firm conclusion regarding anthropogenic changes be made."

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Summary: At this point, it should be clear to the reader that both the Medieval Warm Period and Little Ice Age cannot be dismissed by adroit data averaging, and that far too little importance has been assigned to the effects of solar variations on climate by the IPCC. In addition, the IPCC conclusion that "The observed [twentieth century] warming is inconsistent with *model* estimates of natural internal climate variability" [emphasis added] is of little help to policy makers since—to quote Gerald North of Texas A&M [*Science* **292**, 192 (2001)]—"There are so many adjustables in the models and there is a limited amount of observational data, so we can always bring the models into agreement with the data." The limits of "natural climate variability" are built into the models.

Given the discussion above, policymakers should take great care in using the conclusions of the IPCC in international relations. As the IPCC itself points out, evidence is increasing "that a rapid reorganization of atmosphere and ocean circulation

(time-scales of several decades or more) can occur during inter-glacial periods without human interference."

On a Positive Note

Some very interesting work has been done on determining the disposition of carbon dioxide produced by the burning of fossil fuels. This is contained in Figure 3.4 of *The Scientific Basis* and is reproduced below. It is worth spending some time on this graph, but before doing so some background is needed.

All carbon contained in organic compounds in the biosphere is ultimately derived from photosynthesis, a *simplified* reaction for which is given by

$$6CO_2 + 6H_2O + \text{light} \xrightarrow[\text{chlorophyll}]{} C_6H_{12}O_6 + 6O_2.$$

This chemical equation states that carbon dioxide is taken from the atmosphere and used by chlorophyll in plants to produce glucose (a simple sugar that is often the end product of photosynthesis) plus oxygen, the energy to drive the reaction coming from light. The oxygen on the right-hand side of the equation comes from the water on the left-hand side—not the oxygen contained in carbon dioxide.

Most photosynthesis on land is performed by higher plants while almost all marine photosynthesis is done by single celled organisms known as phytoplankton, examples of which are diatoms and coccolithophorids. *On the average, terrestrial photosynthesis has little net effect on the concentration of atmospheric oxygen because it is balanced by the reverse processes of respiration and decay*. The simplified reaction for this process is

$$CH_2O + O_2 \rightarrow CO_2 + H_2O + \text{energy}.$$

Here CH_2O is the group upon which carbohydrates are based.

Marine photosynthesis is a net source of oxygen because a small fraction, approximately 0.1%, of the organic material produced in the ocean is buried in sediments. "This small leak in the marine organic carbon cycle is responsible for most of our atmospheric O_2." [Kasting and Siefert 2002]

Carbon has two biologically important stable isotopes: carbon 12 (the usual carbon designated ^{12}C) and carbon 13 (designated ^{13}C). The percentages of the isotopes in naturally occurring mixtures are 98.89% and 1.11% respectively. The amount of each isotope of carbon taken from atmospheric carbon dioxide through photosynthesis will vary depending on the type of plant. Consequently, carbon isotope ratio (the ratio of the concentration of ^{13}C to ^{12}C, written $\delta^{13}C$) will be different in terrestrial plants using C_3, C_4, and CAM photosynthesis [See Note 3], and these will differ from aquatic organic carbon sources such as phytoplankton.

Isotope ratios are usually given in parts per thousand (‰) relative to a standard:

$$\delta^{13}C = ((R_{sample} / R_{standard}) - 1) \times 10^3,$$

where $R = {}^{13}C/{}^{12}C$. Plants tend to have less ^{13}C than the standard, and therefore have negative values of $\delta^{13}C$. So how do the different photosynthetic pathways differ in their isotopic carbon ratios, particularly for C_3, C_4, and phytoplankton (these are the important cases for what follows)?

The isotopic composition of carbon dioxide in the atmosphere has a $\delta^{13}C$ of about −6‰ to −7‰. Plants using the C_3 pathway of photosynthesis (most higher plants) have isotopic ratios between −23‰ and −33‰, with an average of about −26‰. Plants using the C_4 pathway (most tropical and marsh grasses) average about −13‰, and range from −9‰ to −16‰. Organic matter in marine phytoplankton shows a range of values between −10‰ and −31‰, with most values lying between −17‰ and −22‰.

The reason that this is important is that a change in atmospheric $\delta^{13}C$ can be used as a measure of terrestrial uptake of carbon dioxide. This follows because the exchange of carbon dioxide with the ocean leaves atmospheric $\delta^{13}C$ unchanged (the validity of this assumption is discussed below), while uptake by plants, since they discriminate against ^{13}C, enriches the $\delta^{13}C$ of the carbon dioxide left in the atmosphere.

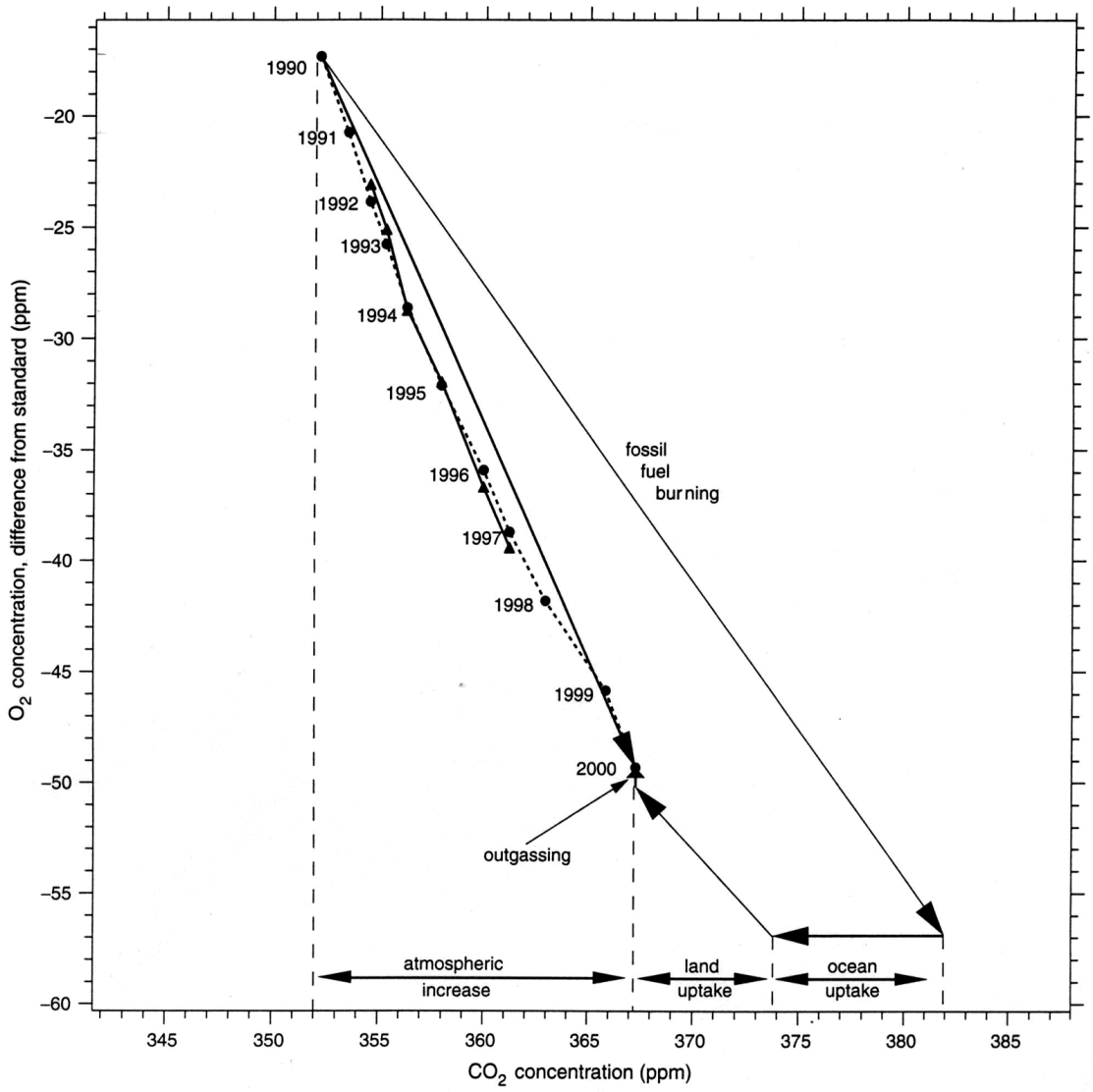

Figure 5: Partitioning of fossil fuel CO_2 uptake using O_2 measurements (Keeling and Shertz, 1992; Keeling et al., 1993; Battle et al., 1996, 2000; Bender et al., 1996; Keeling et al., 1996b; Manning, 2001). The graph shows the relationship between changes in CO_2 (horizontal axis) and O_2 (vertical axis). Observations of annual mean concentrations of O_2, centered on January 1, are shown from the average of the Alert and La Jolla monitoring stations (Keeling et al., 1996b; Manning, 2001; solid circles) and from the average of the Cape Grim and Point Barrow monitoring stations (Battle et al., 2000; solid triangles). The records from the two laboratories, which use different reference standards, have been shifted to optimally match during the mutually overlapping period. The CO_2 observations represent global averages compiled from the stations of the NOAA network (Conway et al., 1994) with the methods of Tans et al. (1989). The arrow labeled "fossil fuel burning" denotes the effect of the combustion of fossil fuels (Marland et al., 2000; British Petroleum, 2000) based on the relatively well known O_2:CO_2 stoichiometric relation of the different fuel types (Keeling, 1988). Uptake by land and ocean is constrained by the known O_2:CO_2 stoichiometric ratio of these processes, defining the slopes of the respective arrows. A small correction is made for differential outgassing of O_2 and N_2 with the increased temperature of the ocean as estimated by Levitus et al. (2000). [Fig. 3.4 and caption from *Climate Change 2001: The Scientific Basis*]

Using $\delta^{13}C$ to measure terrestrial carbon dioxide uptake can serve to corroborate the method used in Fig. 5. There one measures the changes in the ratio of oxygen to nitrogen. For this technique to work, one must assume that nitrogen concentration is constant and that exchange of oxygen with land plants is the only long-term influence on oxygen concentration (see below). The IPCC assumes that ocean uptake of carbon dioxide does not affect the ratio O_2/N_2 so that changes in this ratio are a measure of terrestrial uptake of carbon dioxide. This is a reasonably good approximation, even though—as explained earlier—marine photosynthesis is the source of the earth's oxygen because a small fraction of the organic material produced in the ocean is buried in sediments.

Battle, et al. (2000) using both techniques found that although agreement of the $\delta^{13}C$ and $\delta O_2/N_2$ records is far from perfect, "from 1977 to 1990, the land biosphere was neither a source nor a sink of carbon. In contrast, the first 7 years of this decade [the 1990s] show a significant terrestrial sink of carbon." Note that a net terrestrial uptake of carbon dioxide implies a net release of oxygen. Since, as explained above, over longer periods of time land plants are not a net source of oxygen, a net absorption of carbon dioxide by land plants is either temporary or indicates a significant long-term change in the distribution, type or amount of land plants.

Figure 5 plots the oxygen concentration difference from a standard, since that is what is of interest, although for practical reasons one must measure the ratio of oxygen to nitrogen [see Note 4]. This figure is a vector diagram that tries to account for the difference between carbon dioxide released through the burning of fossil fuels and the rise in atmospheric concentration that is actually observed. It works as follows: The upper arrow or vector from 1990, labeled "fossil fuel burning," represents all the carbon dioxide released since 1990. If no absorption of these emissions had taken place, atmospheric carbon dioxide concentration would have increased by 30 ppm, from 352 ppm to 382 ppm, and oxygen concentration (δO_2—see Note 4) would have changed from about −17.2 ppm to −57 ppm, a decrease of 39.8 ppm. The concentration changes of 30 ppm and −39.8 ppm are respectively the *x* and *y* components of the vector representing carbon dioxide increase and oxygen decrease due to fossil fuel burning in the absence of

carbon dioxide absorption. The vector from 1990 to 2000 represents the *measured* increase in carbon dioxide concentration and decrease in oxygen concentration.

As mentioned in *The Scientific Basis*, the $\delta O_2/N_2$ "method can only distinguish between net non-biological ocean uptake and net biospheric uptake, which in principle includes both the terrestrial and the marine biospheres." The method therefore assumes that the net exchange of oxygen between the marine biosphere and the atmosphere is zero. For the moment, assume this is the case. Then, since we know the change in oxygen concentration (difference from a standard) as measured, and the change in oxygen concentration that should result from fossil fuel burning, the difference between the two—because it is stoichiometrically (in a fixed ratio) linked to the uptake of carbon dioxide—tells us how much carbon dioxide was taken up by land plants. This completely determines the vector in Fig. 5 just above "land uptake." The *y*-component of this vector is the difference between the reduction in oxygen concentration that should be due to fossil fuel burning and that which is actually observed, while the *x*-component is the amount of carbon dioxide absorbed by land plants. The rest of the carbon dioxide must have been taken up by the ocean and is indicated by the vector just above "ocean uptake." This vector has no *y*-component because of the assumption that there is no *net* exchange of oxygen between the ocean and the atmosphere. Except for a small correction labeled "outgassing," one can see that the two vectors representing ocean uptake and land uptake add vectorially to the vector representing fossil fuel burning to equal the vector representing the observed increase of carbon dioxide.

From the figure it can be seen that the ocean and land together take up about 50% of the carbon dioxide released by fossil fuel burning. The figure also indicates that over the period 1990-2000 the land and ocean took up equal amounts of carbon dioxide.

Figure 5 should not leave the reader with the impression that the disposition of carbon dioxide from fossil fuel burning is completely understood. Had Fig. 5 been drawn for the period 1977-1990, when the land biosphere was neither a source nor a sink of carbon, the difference between observed and emitted carbon dioxide would all have to be attributed to uptake by the ocean. However, we know this is not the case since for the period 1980-1989 there is a lack of understanding of the disposition of 23% of the carbon

contained in carbon dioxide emitted by fossil fuel burning and land use changes (see the *Global Warming Primer*).

Keeling, et al. (1996), one of the key sources for Fig. 5, point out that one possible "source of error is the interannual variations in air-sea exchange of O_2 driven by imbalances in marine photosynthesis and ventilation rates," and further note that the O_2/N_2 and CO_2 data alone are not sufficient in general to quantify interannual imbalances in O_2 or CO_2 driven by ocean biota." They state that their analysis assumes these exchanges are small.

The assumption that the marine biosphere does not change in its net exchange of oxygen with the atmosphere may not be on a firm footing. The ratio of carbon, nitrogen and phosphorus (C:N:P) in organic soft tissue is relatively constant and is called the Redfield ratio. There is evidence that carbon consumption in the ocean is significantly in excess of that predicted by the Redfield ratio. The implication is that estimates of ocean uptake of carbon dioxide may be too low. Pahlow and Riebesell (2000) have looked at deep ocean Redfield ratios and concluded that the biological part of the marine carbon cycle is not in a steady state. It is not yet clear how this might affect the analysis above.

Emerson, et al. (2001) found that over the period between 1980 and 1997 there must have been changes in the biological pump or upper-ocean ventilation by as much as 30-50%. *The Global Warming Primer* points out that some 20% of the biological pump's activity takes place at the continental margins, which are the most susceptible to changes resulting from human activity. Yool and Fasham (2001) found that the continental shelves "contribute an estimated 19-28% of total global ocean production." Changes in the flow of nutrients from the land—both natural and anthropogenic—could significantly affect the biological productivity of these regions.

Despite the uncertainties in this work, it has great promise in helping us to understand the carbon cycle. Of particular importance is the fact that independent estimates of the uptake of carbon by the land biosphere and oceans is possible by using measurements of $\delta^{13}C$ and $\delta O_2/N_2$.

The Role of Methane in Climate Change

The concentration of methane (CH_4) in the atmosphere has risen by about 1000 parts per billion (ppb) since 1750 AD to about 1750 ppb. Methane's effectiveness as a greenhouse gas has a dynamic quality since it is oxidized by the hydroxyl ion OH—produced by sunlight acting on water vapor in the troposphere—to carbon dioxide. After a one-time perturbation, it takes 12 years for this process to bring the methane concentration back to equilibrium. As a result, the 20 year global warming potential of methane, on a weight-for-weight basis, is about sixty times that of carbon dioxide while the 100 year potential is about twenty times that of carbon dioxide. The present day warming potential of methane from human activities is almost half that of carbon dioxide [Hansen, et al. (2000)]. Perhaps the most important aspect of methane as a greenhouse gas is that intermittent release of methane from marine sedimentary hydrates may have affected climate greatly several times in the earth's history [D'Hondt, et al. (2002)].

There are enormous quantities of methane beneath permafrost and certain parts of the ocean. For example, the Blake Ridge, located some 300 kilometers off the coast of South Carolina contains some 10^{12} cubic feet of methane, six times the total proven United States reserves of conventional natural gas. The methane is in the form of gas hydrates. These substances are formed by methane and water, usually within sediments that allow the methane concentration to rise above the saturation level of water alone. Such solids are called clathrates. Once formed they can occasionally be found as exposed outcroppings on the sea floor, and are stable in many parts of the ocean. As shown in Fig. 6, they are stable over a wide range of pressures and temperatures.

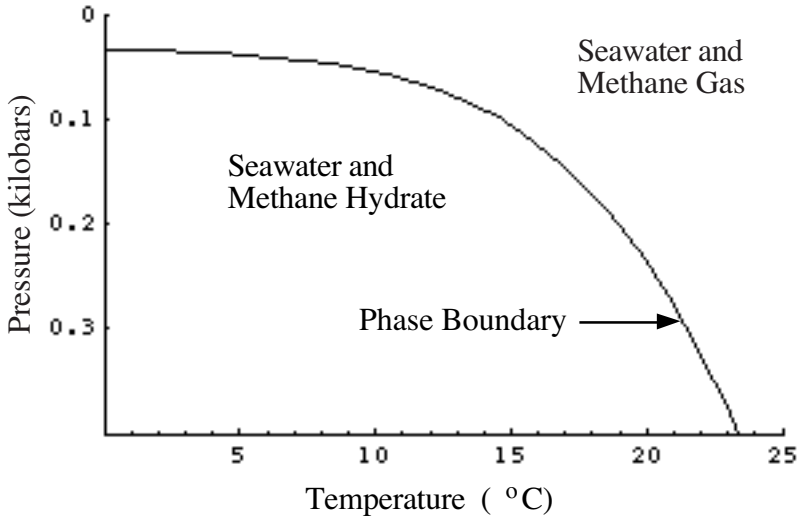

Figure 6. Phase diagram for methane hydrate. The stable region is marked "Seawater and Methane Hydrate." A pressure of 0.1 kilobar is equivalent to an ocean depth of 3300 feet or about 1006 meters.

The world-wide extent of methane clathrates and their characteristics have been discussed by Kleinberg and Brewer (2001). Recent global estimates of methane in hydrate form vary, but are on the order of 10^{16} kilograms.

Many geologists believe the warming of 55 million years ago, in the late Paleocene, was due to the release of methane. Such releases may occur also during an ice age because of the formation of glaciers. As glaciers are formed, the sea level drops thus reducing seafloor pressures and destabilizing the hydrates. The subsequent large-scale release of methane could terminate the ice age.

This possibility is dismissed by the IPCC with the comment that "Brook et al. (2000) find little evidence for rapid, massive CH_4 [methane] excursions that might be associated with large-scale decomposition of methane hydrates in sediments during the past 50,000 years." Nisbet (2000), however, maintains that "Methane emissions from geological reservoirs may have played a major role in the sudden events terminating glaciation," the start of the Bølling-Allerød warm interval at around 14.7 thousand years ago and the Younger Dryas event of some 11 thousand years ago being such examples. Clark, et al. (2002), on the other hand, use the Bølling-Allerød and Younger Dryas events as examples of where abrupt climate change might have occurred as a result of a change in the thermohaline circulation. As will be seen in the next section, there is also evidence

on a longer time scale that methane plays a major role in climate change. Nonetheless, the case for methane driven climate change is far from conclusive. Given its potential impact, however, understanding it is of great importance.

Carbon Dioxide and Climate: A Palaeobotanical View

Retallack (2002) has used a technique that takes advantage of the fact that plant leaves have fewer stomata when atmospheric carbon dioxide concentration is high [Beerling, et al. (1998)] to measure carbon dioxide concentration levels over the last 300 million years. The results are given in Fig. 7, a most interesting and revealing figure.

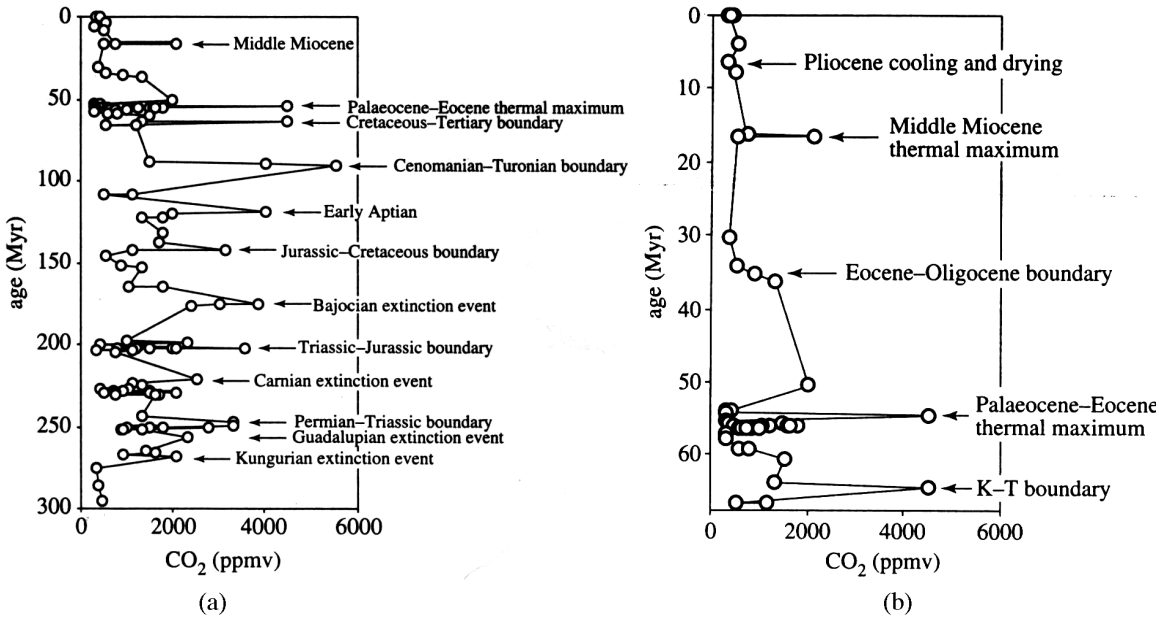

Figure 7. Atmospheric carbon dioxide concentrations over the last 300 million years as estimated from the stomatal index of fossil leaves. [Adapted from Retallack (2002)]

As foreshadowed in the last section, Retallack believes that methane played a significant role in climate change. Biological sources of methane, and in particular the methane contained in methane clathrates is isotopically light and oxidizes to isotopically light carbon dioxide, as discussed above. Retallack maintains that "The carbon isotopic excursion during the terminal Palaeocene is so profound that it can only be explained by

dissociation of isotopically light CH_4 from clathrate deposits . . . [and such] dissociation events are also the only feasible interpretation of large carbon isotopic excursions during the earliest Triassic." Concentrations of carbon dioxide above 2000 ppm are "not only times of catastrophic release of CH_4 from clathrates, but of asteroid and comet impacts, flood basalt eruptions and mass extinctions."

Figure 7 shows that the average atmospheric carbon dioxide concentration was much higher than today until about 35 million years ago. It is significant that this is the time when angiosperms (flowering plants) and in particular grasses became dominant on land.

Interestingly enough, the times of warm ocean temperature correlate very strongly with the times of high atmospheric carbon dioxide as estimated from fossil leaf stomata [see Fig. 8(a)]. In this figure, R^2 is the "coefficient of determination"—the square of the correlation coefficient. An R^2 of 0.99 is a very strong correlation. The uncertainty in the time is greater than a million years, so that a strong correlation does not necessarily imply that the rise in carbon dioxide caused the marine temperature peak.

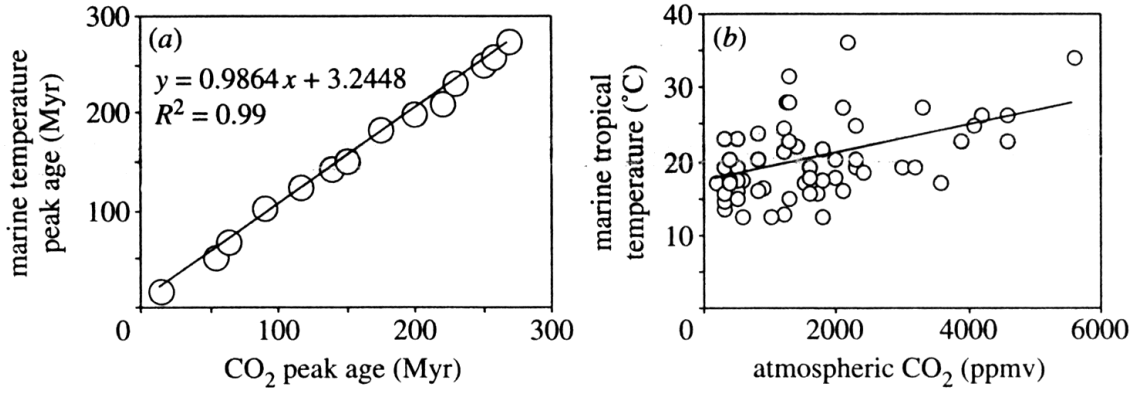

Figure 8. Correlation between (a) the *times* of temperature peaks in the ocean from oxygen isotopic values and *times* of high atmospheric carbon dioxide from leaf stomata; and (b) the *magnitude* of the temperature and carbon dioxide excursions. [From Retallack (2002)]

In contrast with the *times*, the small positive correlation of the *magnitudes* of the temperature and carbon dioxide excursions, as seen in Fig. 8(b), is not significant. Retallack suggests that "The lack of strong correlation between the magnitudes of the

excursions may be because of inadequate sampling of differing sensitivity of either proxy." This is entirely possible. But there is also another possibility.

As explained in the *Global Warming Primer*, natural concentrations of carbon dioxide are great enough in the modern atmosphere that it is opaque even over short distances at the center of the 14.99 micron band, the principal absorption band for infrared radiation. Thus, adding more carbon dioxide to the atmosphere only has an influence at the edges of the band. Because the effect is marginal, the change in forcing due to a change in carbon dioxide concentration is proportional to the natural logarithm of the fractional change in concentration of this gas. The latest IPCC report gives the relation as

$$\Delta F = 5.35 \ln (C/C_0) \text{ w/m}^2.$$

where ΔF is the change in forcing, and C_0 and C are the initial and final carbon dioxide concentrations. This approximation breaks down for very low concentrations and for concentrations greater than 1000 ppmv (parts per million by volume), but is valid in the range of practical interest. The earth's temperature is therefore relatively insensitive to changes in carbon dioxide concentration, a doubling leading to a ΔF of only 3.7 w/m^2, about 15% less than the IPCC's earlier estimate of 4.37 w/m^2.

At the carbon dioxide concentrations of interest in Retallack's work, such a simple formula could no longer be expected to be valid. The lack of strong correlation shown in Fig. 8(b) could well be due to the absorption line at 14.99 microns being essentially saturated to the edges of the band, not only near the center. Even at the exceptionally high concentrations of carbon dioxide of over 4000 ppmv (more than 10 times today's concentration) the data show marine tropical temperatures did not exceed about 25 °C.

SUMMARY

Even from this limited critique, looking only at a few topics covered in the latest report of the IPCC, it should be obvious that the modeling uncertainties are still so great

that the claim by the IPCC that "most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" is "likely" to be unfounded. Remember, by the IPCC criteria "likely" means that there is a 66-90% chance that the statement being made is true.

The latest IPCC report is far more extensive and comprehensive than earlier reports, and demonstrates that some fine research is being done. Nevertheless, the many uncertainties that remain indicate that our understanding of the earth's climate is not yet adequate to let us assess the long-term effects of carbon dioxide released in burning fossil fuels. Model predictions are still too unreliable to serve as a basis for public policy decisions.

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NOTES

1. Nathan Mantua of the Joint Institute for the Study of the Atmosphere and Oceans (University of Washington, Seattle, Washington), has given a general summary of what is known about the Pacific Decadal Oscillation: "Fisheries scientist Steven Hare coined the term 'Pacific Decadal Oscillation' (PDO) in 1996 while researching connections between

Alaska salmon production cycles and Pacific climate. PDO has since been described as a long-lived El Niño-like pattern of Pacific climate variability because the two climate oscillations have similar spatial climate fingerprints, but very different temporal behavior. Two main characteristics distinguish PDO from El Niño/Southern Oscillation (ENSO): first, 20th century PDO 'events' persisted for 20-to-30 years, while typical ENSO events persisted for 6 to 18 months; second, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics—the opposite is true for ENSO. Several independent studies find evidence for just two full PDO cycles in the past century: 'cool' PDO regimes prevailed from 1890-1924 and again from 1947-1976, while 'warm' PDO regimes dominated from 1925-1946 and from 1977 through (at least) the mid-1990's (Mantua et al. 1997, Minobe 1997). Minobe (1999) has shown that 20th century PDO fluctuations were most energetic in two general periodicities, one from 15-to-25 years, and the other from 50-to-70 years. . . . Causes for, and the potential ability to predict, PDO are not currently known. . . . From a societal impacts perspective, recognition of PDO is important because it shows that 'normal' climate conditions can vary over time periods comparable to the length of a human's lifetime."

2. To obtain the value of 0.3 Wm^{-2} for the change in solar radiative forcing since 1750, the IPCC used the difference between the TSI values at the 11-year solar cycle minima of 1744 and 1996, taken from Fig. 3. Note that the figure shows total solar irradiance (TSI). To convert to solar radiative forcing, as discussed in the *Global Warming Primer* and noted in section 6.11.1.1 of *The Scientific Basis*, "Geometric factors affect the conversion from change in TSI to radiative forcing. It is necessary to divide by a factor of 4, representing the ratio of the area of the Earth's disc projected towards the Sun to the total surface area of the Earth, and to multiply by a factor of 0.69, to take account of the Earth's albedo of 31%. Thus a variation of 0.5 Wm^{-2} in TSI represents a variation in global average instantaneous (i.e. neglecting stratospheric adjustment) radiative forcing of about 0.09 Wm^{-2}."

3. CAM stands for Crassulacean Acid Metabolism. It is a dry-climate variation of photosynthesis found in succulents. These plants (called Crassulaceae) close their stomata during the day and open them at night. The carbon dioxide needed for photosynthesis is taken in at night and stored until the daytime where it is used in C_3 photosynthesis. CAM photosynthesis evolved independently of C_4 photosynthesis, the other plant adaptation to dry climates (see the *Global Warming Primer* for a discussion of C_3 and C_4 photosynthesis).

4. Changes in atmospheric oxygen due to fossil fuel burning are very small and very difficult to measure. Keeling and Shertz (1992) used an interferometric technique [Keeling, R.F., *J. Atmos. Chem.* **7**, 153 (1988)] to do their measurements. The conversion of $\delta O_2/N_2$ to $\delta O2$ is done by using the formula for relative deviations of a ratio from a reference (here one multiplies by 10^6 to express the result in "per meg" or parts per million changes in a ratio):

$$\delta O_2/N_2 = ((R_{sample} / R_{standard}) - 1) \times 10^6,$$

where $R = O_2/N_2$. By expressing R_{sample} as the ratio of the oxygen concentration of the standard minus the difference from the standard to nitrogen; i.e., $(O_2 - \delta O_2)/N_2$, and solving for δO_2, one finds that

$$\delta O_2 = 0.209 (\delta O_2/N_2).$$

The factor 0.209 comes from the fact that oxygen makes up 20.9 % of the atmosphere.