COMPARISON OF SOLAR AND OTHER INFLUENCES ON LONG-TERM CLIMATE*

James E. Hansen, Andrew A. Lacis and Reto A. Ruedy

Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025

In this paper I first show examples of climate variability and discuss unforced climate fluctuations, as evidenced in both model simulations and observations. I then compare different global climate forcings, a comparison which by itself has significant implications. Finally, I discuss a new climate simulation for the 1980s and 1990s which incorporates the principal known global climate forcings. The results indicate a likelihood of rapid global warming in the early 1990s.

1. INTRODUCTION

I got a little worried yesterday afternoon when I started to think about what talk I could give today. I had brought a pile of viewgraphs from my office, thinking that I would be able to select several to make a decent talk — with the idea of comparing possible solar-forced climate change with climate change due to other forcings, and comparing all of these with unforced climate fluctuations. That may sound o.k., but when I looked at my viewgraphs, they seemed pretty dull to me.

However, after thinking about them awhile, I realized that they lead to a remarkable conclusion, one with political and social implications. And, surprisingly, the result derives, in part, from the little one-tenth of one percent change in the solar irradiance measured by Dick Willson, which is usually dismissed as of no climatic importance.

So if you stick it through, you may find the conclusion interesting. I can't guarantee that I will convince you of the conclusion. But I'm pretty sure that it is right. In fact, if you disagree with it, I would be happy to make a friendly little wager—one which much of the community apparently believes to be very improbable, so perhaps it's a good chance for you to take my money.

2. OBSERVED CLIMATE VARIABILITY

The first viewgraph (Fig. 1) shows temperature variations over the past 160,000 years, as inferred from isotopes in an ice core from Antarctica. The temperature thus refers to this specific region, at the level in the atmosphere where the snow formed.

A smoothed estimate of global temperature over the same period is shown in Figure 2. Global temperature fluctuates on this time scale by about 5C

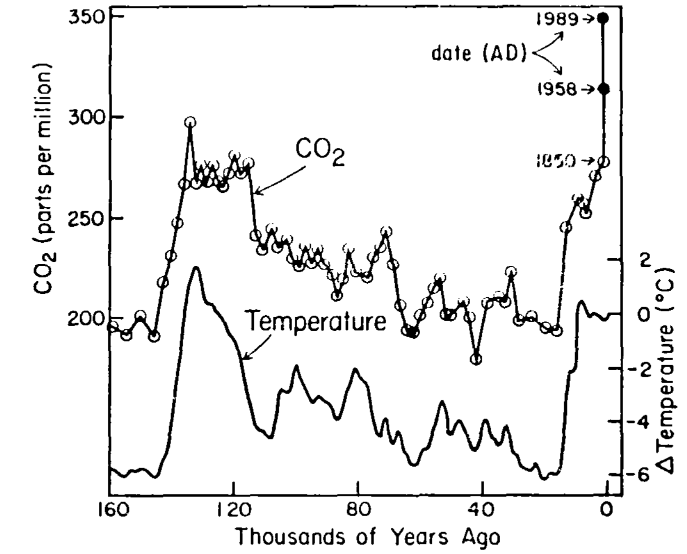

Fig. 1. Atmospheric CO_2 and temperature change in the past 160,000 years as inferred from Soviet/French Vostok Antarctic ice core. Twentieth century data points are based on Keeling's measurements.

between the interglacial periods and the depths of the glacial periods. Similar oscillations of global temperature have occurred many times over the past few million years.

These glacial to interglacial climate fluctuations appear to be related to a certain type of solar variation — the seasonal and geographical redistribution of insolation caused by changes in the Earth's orbital elements (the eccentricity of the orbit, the tilt of the spin axis, and the season of periapsis). Specifically, a high correlation is found between the climate changes and the changes of the Earth orbital elements, and thus the latter are called the "pacemakers of the ice ages."

However, the orbital changes by themselves cause very little net heating or cooling averaged over the year and over the planet. The mechanisms which maintain the global temperature can be investigated by examining the glacial to interglacial change of the

*This paper is the talk given by one of us (JEH) at the conference Climate Impact of Solar Variability, NASA Goddard Space Flight Center, Greenbelt, Maryland, April 25, 1990, with two added explanatory notes.

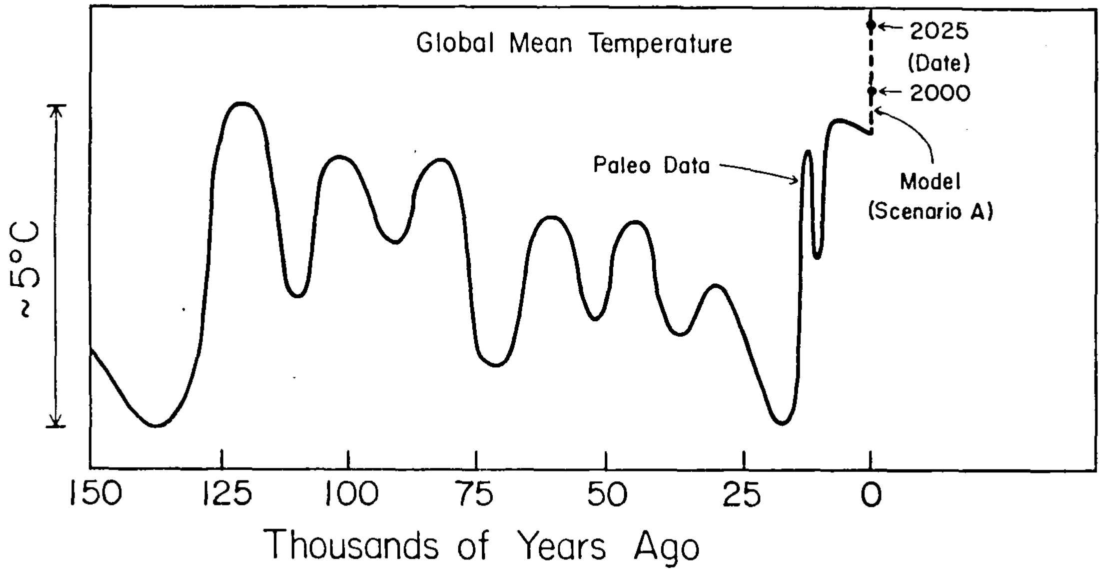

Fig. 2. Smoothed estimate of global temperature change over the past 150,000 years, and a projection assuming continued rapid growth of greenhouse gases.

planetary radiation balance. It turns out that the principal factors maintaining the ice age cold were, (1) the increased area of ice sheets and snow, which reflected sunlight to space, (2) decreased amounts of atmospheric carbon dioxide and methane, which reduced the greenhouse effect, and (3) increased amounts of aerosols and dust, which also reflected sunlight.

Most likely, these mechanisms were feedbacks, that is processes which amplified a tendency for climate change driven by the earth orbital elements or other factors. Indeed, although the fluctuations appear to be almost synchronous (Fig. 1), the carbon dioxide change usually lags slightly behind the temperature change, as expected for a feedback.

Figure 3 shows global temperature on the 100 year time scale, based on the network of meteorological stations. There are several issues about this record, especially (1) whether the station coverage is adequate to estimate global trends, and (2) whether the station records contain systematic biases, such as urban warming. The error due to incomplete spatial coverage can be estimated quite well from knowledge of spatial and temporal variability of temperature and has been shown to be reasonably small, as indicated by the error bars (Fig. 3). Urban effects on the global temperature change have been estimated in several different ways and found to be not larger than 0.1–0.2C.

It is apparent that over the full century there is a substantial warming trend. However, within that period there are intervals of cooling, most notably the cooling trend from about 1940 to 1970. There are also year to year fluctuations as large as a few tenths of a degree. Within the 1980s the maxima in 1983 and 1987–88 are associated with major El Niños, as evidenced by the spatial pattern of the warming.

Note that there is no significant trend of global temperature within the 1980s. Recently great publicity was given to an apparently surprising result: "satellites find no warming in the 1980s." This statement was bound to deceive the public, because of all the prior publicity about the 1980s

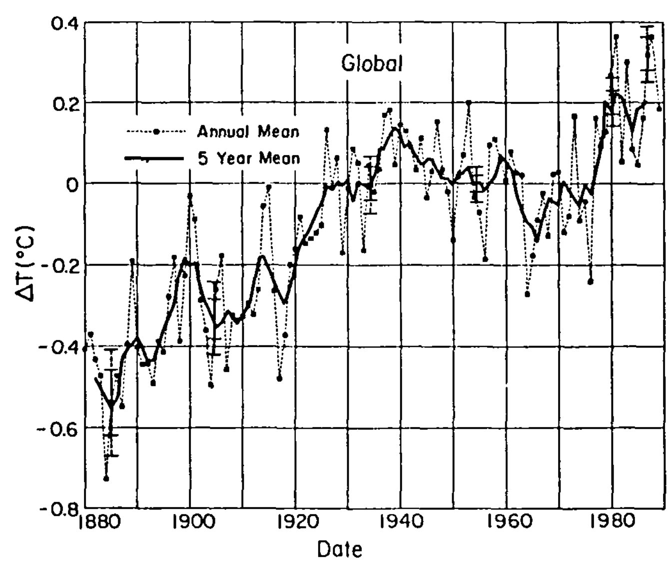

Fig. 3. Global temperature change of the past century based on measurements at meteorological stations.

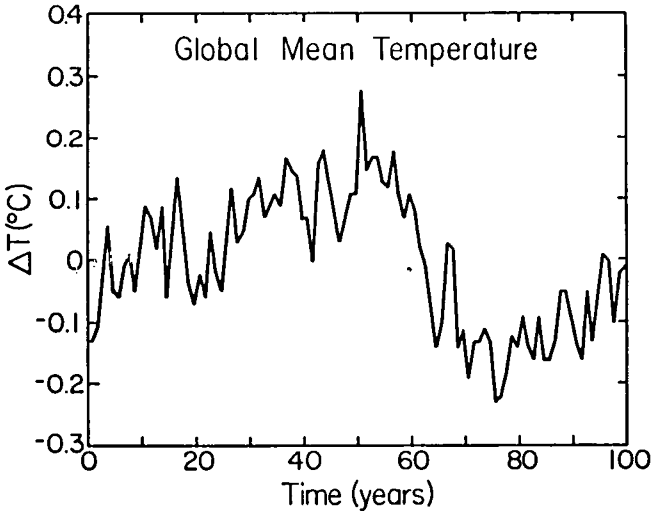

Fig. 4. Global temperature in 100 year run of a climate model with no variations of climate forcing.

being the warmest decade of the century with the several warmest years all in the 1980s. In reality, of course, there was no contradiction with the previous findings; the satellite record was simply too brief to be used for studying long term trends.

Also note that even the investigators' optimistic estimate of the satellite error as being 0.005C/year corresponds to 0.5C/century, an error which would mask the trend of the past century. This large error does not mean that the satellite data are of no value for study of long term climate change. On the contrary, an improved observing system would involve a combination of satellite data, to provide nearly global coverage, and a continuation of surface and upper air (radiosonde) measurements at meteorological stations, to provide absolute calibration and a continuation of long term records.

3. UNFORCED CLIMATE FLUCTUATIONS

Climate fluctuates without any change of climate forcing. The climate fluctuations arise because the coupled non-linear equations describing atmospheric structure and motion are unstable to small perturbations. In effect, the atmosphere and ocean do a lot of sloshing around. Some of the sloshing, for example, the El Niño/Southern Oscillation phenomena, may be predictable on a limited time scale, but most of it is of a chaotic nature for which long term prediction is only possible in a statistical sense.

Unforced climate variability can be studied to a degree with global climate models, even if the ocean dynamics is fixed. Figure 4 shows the global mean temperature simulated in a 100 year run of our GCM

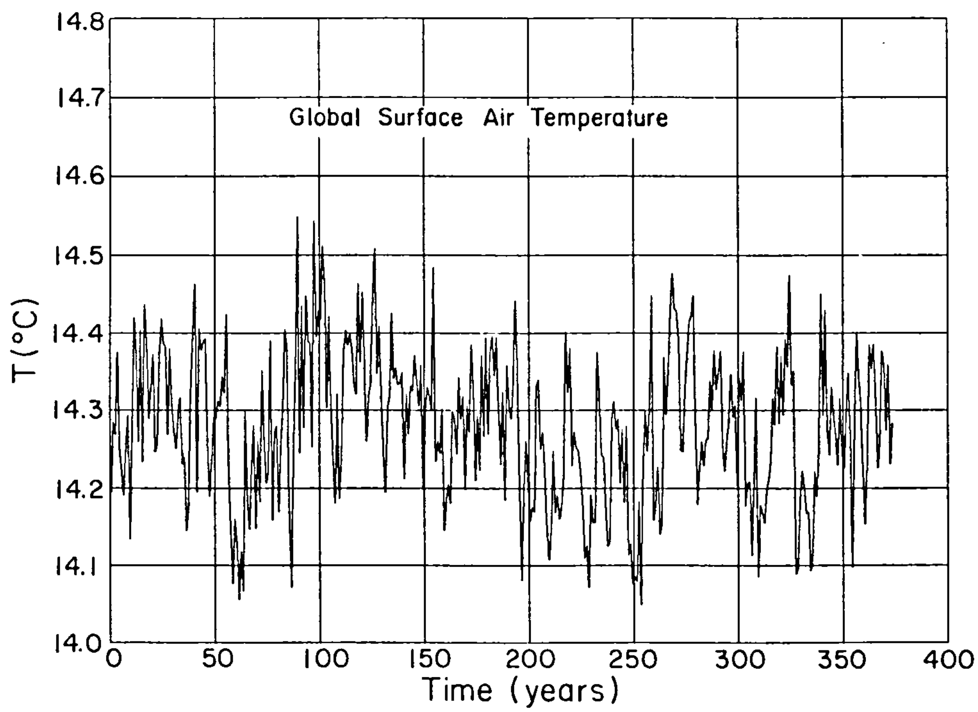

Fig. 5. Global temperature in a long run of a climate model (see Endnote 1) with no variations of climate forcing.

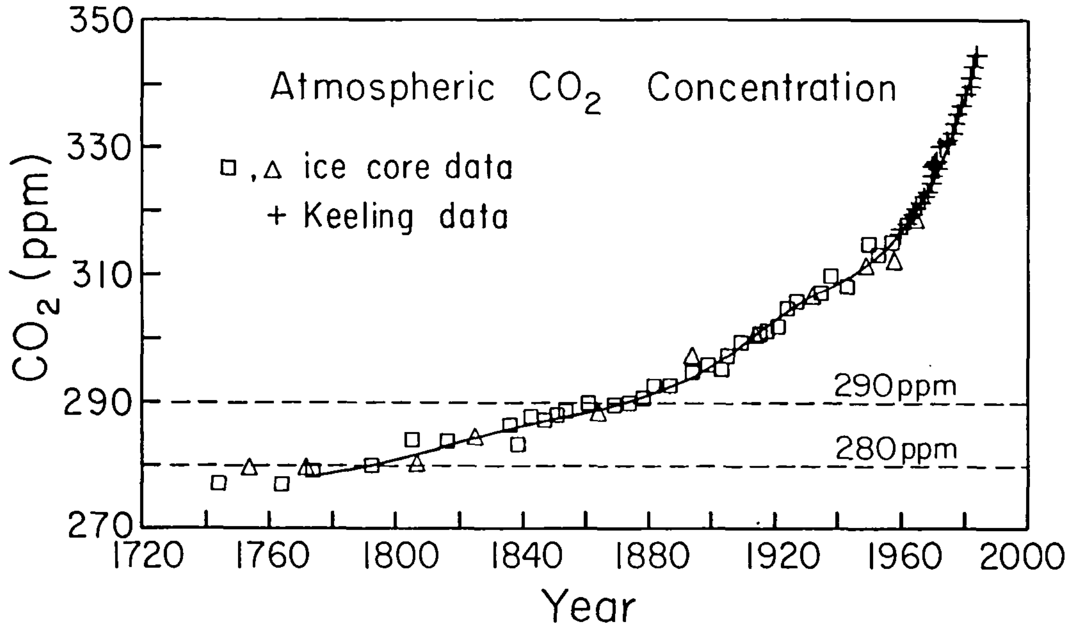

Fig. 6. Atmospheric CO_2 concentration based on ice core data (triangles and squares) and data from Mauna Loa (crosses).

with the solar irradiance and atmospheric composition (except water vapor) fixed, but with ocean temperature computed. Several fast feedback processes, such as atmospheric water vapor amount, cloud cover, and sea ice distribution were free to vary, but the solar irradiance, atmospheric CO_2 and other trace gases, and ice sheet area were fixed. The global mean temperature in this 100 year control run, without climate forcings, varied by as much as several tenths of a degree Celsius, with fluctuations from year to year as well as trends over periods of decades.

We have also made a longer control run, without any change of climate forcings, with a slightly modified version of our GCM (see Note 1). The global mean temperature in this longer run (Fig. 5) has year to year and decadal variations, as in the 100 year run (note that the compressed horizontal scale in Fig. 5 makes the variations appear steeper), but it also shows trends on longer time scales, such as the cooling from year 100 to year 250.

It's instructive to consider how these unforced climate fluctuations would differ if we allowed additional feedbacks to operate, particularly feedbacks which are expected to be significant on paleoclimate time scales. Empirical data indicate that on long time scales ice sheet area tends to decrease with increasing global temperature, and the abundance of the greenhouse gases CO_2 and CH_4 tends to increase with increasing global temperature, so both mechanisms are probably positive feedbacks on paleoclimate time scales. Changes of vegetation cover and atmospheric aerosol amount are more variable, and do not appear to have as large a global impact. Overall, it appears that long time scale feedbacks could make unforced climate fluctuations even much larger than those in Figs. 4 and 5. It is difficult to model the variations of these factors, because we do not understand the mechanisms well enough. But it is likely that unforced climate fluctuations are quite large on paleoclimate time scales.

Unforced climate fluctuations complicate the search for any forced climate change such as may arise from changes of solar irradiance and anthropogenic greenhouse gases. Changes of ice sheet area can be ignored on decadal time scales, and changes of CO_2 and CH_4, although they may be in part a result of climate feedbacks, are known accurately from observations. But one variable ignored in our climate simulations, fluctuations of ocean heat transports, is clearly a significant contributor to global temperature fluctuations.

For example, in the record of observed global temperature for the past century (Fig. 3) the two major El Niños of the past decade show up as relative maxima in 1983 and 1987–88. Ocean transport variability also probably contributes to some of the longer time scale variability in this global temperature record, but we have no proof of that. The standard deviation of global annual mean temperature in our GCM without forcing and with fixed ocean heat transports is about 0.1C. As expected, the standard deviation for the observations is larger, being about 0.15C even if the long term trend in the data is removed. At least in part, the larger variability in the observations is probably due to interannual fluctuations in ocean transports.

4. CLIMATE FORCINGS

A climate forcing, natural or anthropogenic, is a change imposed on the climate system which modifies the planetary radiation balance, thus affecting the planetary temperature. The natural forcings which appear to most significant, based on systematic comparison of radiative effects, are changes of stratospheric aerosols due to large volcanoes and changes of solar irradiance. The largest anthropogenic forcings appear to be increasing infrared-absorbing (greenhouse) gases, man-made tropospheric aerosols, and perhaps changes of surface reflectivity due to desertification and deforestation.

Most of the greenhouse gas changes are known rather well. For example, the CO_2 changes over the past 250 years are shown in Fig. 6. Changes of the other major greenhouse forcings, chlorofluorocarbons, methane, and nitrous oxide, are known reasonably well also.

The net climate forcing by CO_2, CFCs, CH_4 and N_2O for the period from 1958 (the International Geophysical Year, when Keeling began his measurements) to the present is more than 1 W/m^2 (Fig. 7). This is the rate of heating of the Earth's troposphere as computed with a simple (one-dimensional radiative-convective) or a more sophisticated (three-dimensional) climate model for the indicated changes of these gases. The increase of greenhouse forcing between 1850 and the present is more than 2 W/m^2 (Fig. 7). The uncertainty in the radiation calculations is perhaps 10–20%. The uncertainty due to other, unmeasured greenhouse gases, particularly upper tropospheric ozone (which could cause either a heating or cooling) or stratospheric water vapor (which is suspected of increasing due to oxidation of increasing methane), is perhaps another 10–20%. We conclude that there has been a steady increase in the anthropogenic greenhouse gas climate forcing, which has now reached a level of about 2-2.5 W/m^2.

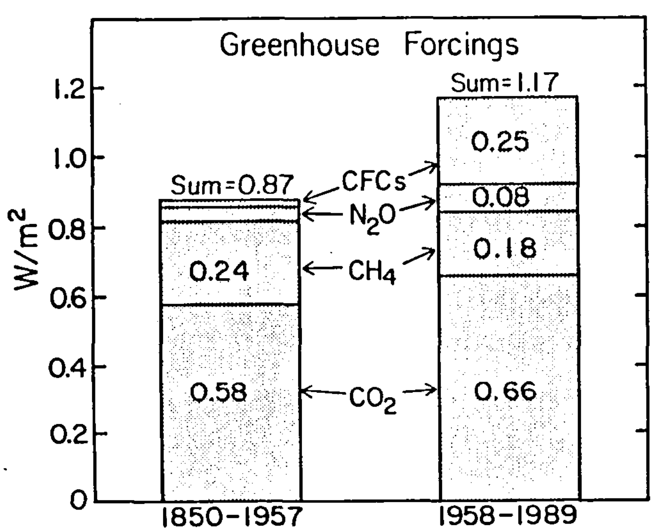

Fig. 7. Added greenhouse climate forcings for the periods 1850-1957 and 1958-1989.

Unfortunately, the anthropogenic aerosol forcing is much more uncertain, and its present trend is unknown. Perhaps as much as 25–50% of present tropospheric aerosols are anthropogenic, which would be a global climate forcing between -0.5 W/m^2 and -1 W/m^2, i.e., a cooling which would balance a significant fraction of the greenhouse warming. Moreover, these aerosols are believed to increase cloud reflectivity, causing further, but very uncertain, negative climate forcing. But aerosol observations are too sparse to define the net aerosol climate forcing. Based on the fact that most anthropogenic aerosols are in the Northern Hemisphere and observations show comparable warming trends in both hemispheres over the past century, it has been argued that the net aerosol forcing must be significantly less than the greenhouse forcing. But clearly we need better global tropospheric aerosol measurements.

Other important climate forcings include changes of stratospheric aerosols and solar irradiance, as illustrated in Fig. 8 for much of the past decade. A solar irradiance change of 0.1% yields a climate forcing equivalent to about a 15 ppm CO_2 change, while at its maximum the global climate forcing of El Chichón aerosols was equivalent to a more than 100 ppm CO_2 change. Of course greenhouse, aerosol and solar forcings of equal global magnitude would not yield identical climate changes. But tests with our GCM using equivalent forcings, namely 2% solar constant change, doubled CO_2, and a change of stratospheric aerosol optical depth of 0.15, yielded generally similar global climate changes (with added aerosols causing *cooling*). Although climate sensitivity is uncertain by perhaps a factor of three, this uncertainty applies equally to all of the forcings.

Solar and greenhouse forcings during their periods of precise monitoring are contrasted in Fig. 9. Over the common period of accurate solar and greenhouse data the changing sun significantly modulates the net climate forcing, but it does not alter the overall trend. *[The upper two solar curves in Fig. 9 use the annual mean and monthly mean of the present official results of the Nimbus 7 ERB, as available from the National Space Science Data Center and described by Hickey *et al.*, *Space Sci. Rev.*, **48**, 321, 1988. The lower curve is an alternate preliminary reduction of the Nimbus 7 data which includes some modifications aimed chiefly at correcting for variations in telescope pointing, as described by D.V. Hoyt and H.L. Kyle (private communication) in a manuscript which will be submitted for publication. Uncertainties in data reduction and calibration, as well as significant differences between Nimbus 7, SMM and ERBE solar irradiance data, highlight the difficulty in achieving the high accuracy needed for climate studies. Adequate monitoring of long term solar change requires having two well-calibrated radiometers in space simultaneously with frequent solar observations, as discussed below. Observing capability during the period 1978–1989 was sufficient to conclude with a high degree of confidence that there was a decline of total solar irradiance of the order of 0.1% during the first several years of this period and at least a partial recovery in the late 1980s.]

Stratospheric aerosol and greenhouse forcings are contrasted in Fig. 10. The aerosol forcing is based mainly on estimates of atmospheric transparency obtained at astronomical observatories. This stratospheric aerosol forcing, which is mostly a result of volcanic eruptions, at times rivals or exceeds the greenhouse forcing, but the latter clearly dominates the long term trend.

Comparison of climate forcings, as in Figures 9 and 10, exaggerates the importance of high frequency variability. Because of the inertia of the climate system, brief forcings have much less impact than those maintained for several decades. Nevertheless, it is apparent that both solar and volcanic aerosol variations potentially are significant causes of climate variability.

Ground-based measurements of solar irradiance and solar diameter during the past 200 years have

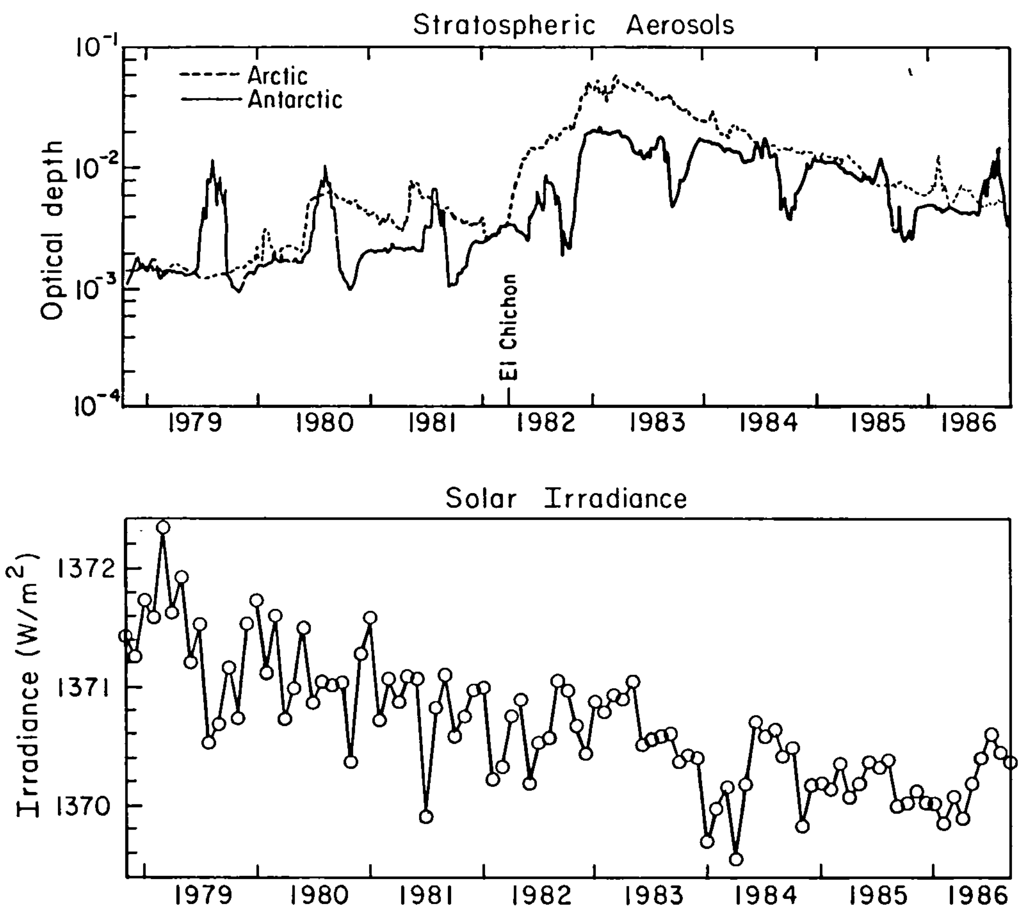

Fig. 8. Stratospheric aerosol optical depth measured by the SAM II instrument and solar irradiance measured by the ERB instrument on the Nimbus 7 spacecraft (SAM II data from P. McCormick; ERB data from J. Hickey, B. Alton, H.L. Kyle and D. Hoyt, as described in *Space Science Reviews*, 48, 321–342, 1988).

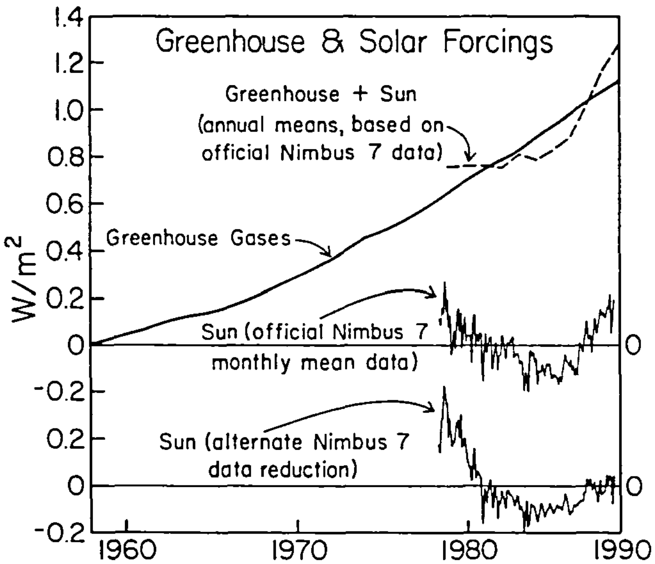

Fig. 9. Greenhouse and solar climate forcings in the past three decades. Solar forcing is based on Nimbus 7 ERB data (see parenthetical comment* in text).

placed an upper limit of about 0.3% on solar variability during that period. However, that degree of variation is sufficient to leave the sun as a candidate for causing the 1940–1970 global cooling, if indeed that was a forced climate change. Moreover, a solar decline of 0.3%, if maintained on a century time scale, would cause a cooling of about 0.5C, if climate sensitivity is 3–4C for doubled CO_2. Since 0.5C is about the magnitude of estimated global cooling during the Little Ice Age, the sun is a viable candidate for forcing that climate fluctuation.

We conclude that solar variability may be a significant climate forcing mechanism, so it is important to maintain accurate solar monitoring. Unfortunately, the most precise solar irradiance data terminated as the Solar Maximum Mission was brought down by atmospheric drag in 1989. Hopefully the solar instruments on Nimbus 7 and the Earth Radiation Budget satellites will continue to function until the planned 1991 launch of the Upper Atmospheric Research Satellite, with its active cavity radiometer. The Nimbus 7 instrument has been a remarkable workhorse over more than 11 years, but it can not measure long term degradation of its sensor. The SMM experiment carried three sensors with two of them normally shuttered, thus allowing occasional calibration of solar-induced degradation of the sensitivity of the primary sensor. A degradation of 0.05% was measured over the 9½ year lifetime of SMM, and this instrument's self-calibrated irradiance was useful for comparison with the simultaneously operating Nimbus 7 instrument. The ERBE instruments presently provide a cross-check on Nimbus 7, but their data have a higher noise level because of a low frequency of solar viewing and other factors. We need to strive to have two well-calibrated instruments simultaneously in orbit, to provide a cross-check and continuity of calibration when an instrument ceases operation.

Finally, I mention one other conclusion which follows from comparison of the above climate forcings. The opinion has been expressed, in a report of the Marshall Institute, that greenhouse warming may be beneficial because it might just cancel cooling in the 21st century due to a declining solar irradiance. But it is apparent that the equivalent of doubled CO_2, which is expected by the middle of next century if there are no reductions in greenhouse gas emissions, would require that solar irradiance decline by 2% to counter the greenhouse climate forcing. While such a solar decline is not strictly impossible, it is much larger than existing indications of solar variability. Given available scientific evidence, it would be foolish to base greenhouse policy on the hope that solar variability will somehow counter greenhouse warming.

5. CLIMATE SIMULATION

We carried out one new climate simulation for this conference. This calculation focused on the past decade and the next few years, for the purpose of

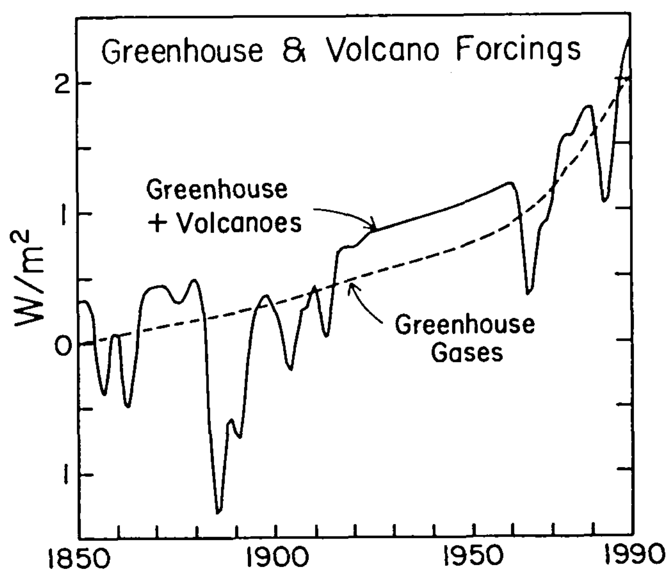

Fig. 10. Greenhouse and stratospheric aerosol climate forcings in the past century. Aerosol optical depth is based mainly on atmospheric transmission measurements at astronomical observatories and lunar eclipses. Zero point of aerosol forcing is the 1850-1989 mean.

examining the climate implications of recent information on changes of solar irradiance and other climate forcings during the 1980s. The new calculation builds on a base of earlier calculations (*J. Geophys. Res.* **93**, 9341, 1988) and uses the same climate model. The previous simulations used a range of scenarios for greenhouse gas changes (A, B and C) and a rough estimate of stratospheric aerosol optical depth following El Chichón, which erupted less than a year before the simulation was started. Greenhouse gases and stratospheric aerosols were the only changing climate forcings in the earlier simulations.

The greenhouse gas forcing in the new simulation, labeled B_n, is based on our recent calculation (*J. Geophys. Res.* 94, 16417, 1989) of the combined forcing by CO_2, CFCs, CH_4 and N_2O, and is almost identical to scenario B of the previous study. Both B and B_n assume linear growth of greenhouse forcing in the future, as opposed to the exponential growth of scenario A ("business as usual") and the eventual no-growth of scenario C ("draconian emission cuts"). Scenarios B and B_n appear to be more realistic than scenarios A and C for recent and near future changes of greenhouse gases.

The solar irradiance was constant in scenario B, i.e., there was no solar forcing. In scenario B_n we used an analytic approximation for satellite measurements of solar irradiance as suggested to us by Dick Willson: a cosine function with full amplitude 0.1%, period 10.95 years, and maximum at 1980.82. Good data through the present solar maximum may allow an improved representation, but this approximation should be sufficient for our present purposes.

The stratospheric aerosols in scenario B are described in our 1988 paper. Scenario B_n uses aerosol opacities derived from approximately annual lunar eclipse data of Richard Keen (*Science*, 222, 1011, 1983 and private communication). The B_n aerosols have a larger maximum optical depth (0.12) than the B aerosols and do not decrease quite as rapidly, so the B_n aerosols tend to give somewhat more cooling in the middle 1980s. For aerosols, we are not certain whether B or B_n is more accurate. Presently we are working with Jim Pollack and Pat McCormick to use a number of data sources to try to define the aerosol forcing more precisely. The net impact of the changes of climate forcing in B_n, as compared to B, is a slightly increased forcing around 1980, a decrease in the middle 1980s, and an increase

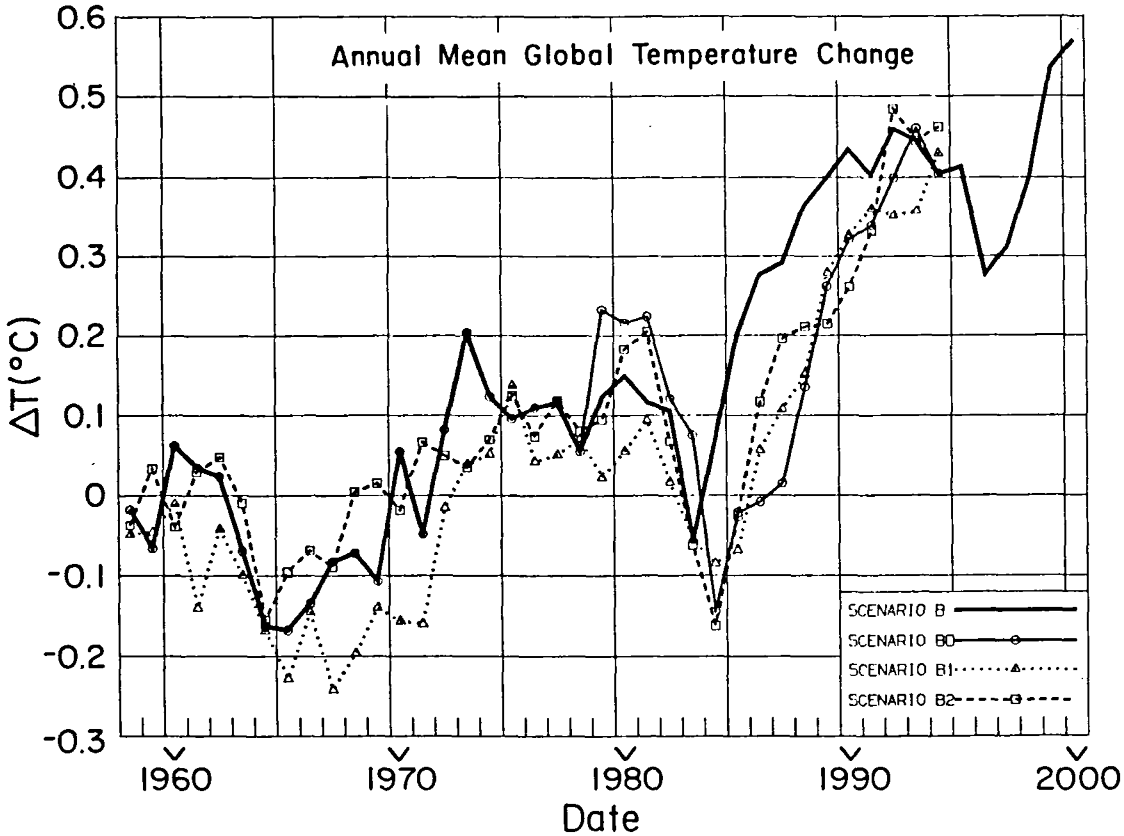

Fig. 11. Global temperatures for three new runs (B_n) of model II compared to previously published scenario B.

at the end of the 1980s and early 1990s.

One point we want to stress is the "butterfly effect." If a climate model simulation is repeated, with identical climate forcing but with some initial atmospheric parameter (temperature, wind, etc.) changed ever so slightly (a flap of a butterfly's wings in Buenos Aires), the simulations follow different chaotic paths. Thus we must make several runs of the model, if we wish to draw any conclusions about climate change on time scales of several years.

We illustrate the global temperature for three new runs of the model (B_0, B_1 and B_2) in Figure 11, along with the published run, scenario B. The B_1 and B_2 runs begin on January 1, 1958 with the same initial conditions as run B except for a slight noise added to atmospheric temperatures. Since the forcings for B and B_n are almost identical for the period 1958-1978, the results for B, B_1 and B_2 in that 20 year period give an indication of the range of chaotic behavior of the model. Run B_0 starts in 1978 and uses B_n climate forcing (its initial state is identical to run B on January 1, 1978).

Note that all the simulations show some response (cooling) to the large short-term negative climate forcings caused by the large volcanoes in 1963 (Agung) and 1982 (El Chichón). Of course the model does not contain the variability associated with fluctuations in ocean heat transports, such as El Niños. Thus, although the real world (Fig. 3) shows clear evidence of cooling after Agung, apparent cooling in the 1982-1985 time frame is interrupted by an intense El Niño warming in 1983.

The dominant feature of the new simulations (runs B_0, B_1 and B_2) is the very strong warming in the late 1980s to a level in the early 1990s clearly above any earlier global temperature. The magnitude of the warming exceeds the noise level of the model. The principal change in scenarios B_n, as compared to B, is a pushing back of the warming by about 2 years to the end of the 1980s. However, both B and B_n reach very high global temperatures, about 0.4C above the level of the 1950s, in the early 1990s.

What assumptions does this result depend upon? *First*, model sensitivity: our model has a sensitivity 4C for doubled CO_2. Any sensitivity in the range 2 to 5C is consistent with empirical data, such as that provided by paleoclimate studies. A sensitivity toward the lower end of this range would reduce the predicted warming, but not by so much as the ratio of sensitivities. Calculations should be carried out with a lower sensitivity, but we do not expect the qualitative prediction to change. *Second*, neglect of other unknown forcings: there are a number of poorly known forcings, such as anthropogenic tropospheric aerosols, sulfate alterations of cloud properties, and aircraft contrails, for example. But the evidence, as we have discussed, suggests that the anthropogenic greenhouse is the dominant forcing. A large volcano could change this picture, but their frequency, several per century, makes an occurrence unlikely in the next year or two. *Third*, neglect of unforced natural cooling. Actually our "butterfly" range of experiments accounts for much unforced variability. The El Niño cycle is probably the main unaccounted unforced variability, and the Earth has just come through the cool (La Niña) phase of that cycle, so, if anything, the El Niño is likely to add to warming in the next 1-3 years. The possibility of a sudden "flip" of ocean circulation, as discussed by Broecker, seems slim on the time frame of the next 1-3 years, and there is little reason to believe such an occurrence would lower global mean temperature.

6. DISCUSSION

My conclusion is that we are likely to set a modern global temperature record in the next 1-3 years, measurably exceeding the already high levels of the 1980s. I described this, in the introduction, as a remarkable conclusion because it is even more immediate and specific than our previous conclusion that the 1990s would see a record temperature level. And other scientists, although most are in agreement that the greenhouse effect will eventually cause global warming, have been unwilling to conclude even that we should expect record warmth in the 1990s. This reluctance is usually based on the observation that natural fluctuations are large in decadal periods, and the fluctuations are toward cooling as often as toward warming. What is overlooked, I believe, is the fact that the present climate is out of equilibrium with current atmospheric composition. Because of that, it is difficult for global temperature to maintain a large "fluctuation" in the direction of lower temperature. Indeed, that point is illustrated by our "butterfly" experiments. And even if we insert a volcano of El Chichón magnitude in 1995, as we did in our 1988 paper, the 1990s are warmer than the 1980s in the model.

Are there political and social implications to be drawn from this conclusion, without stretching it too far? The results suggest that a candidate for election in 1992 may be making a serious mistake if he argues that this is a time only for research and not to take action to slow emissions — because there is a very good chance that he would get burned before the 1992 election, burned by empirical evidence of a warming world. To be burned badly would require some large regional climate impacts as well, but the chance of that happening will rise with increasing global temperature. A social implication follows from the observation that serous attempts to control greenhouse gas emissions will be strongly resisted, and thus hypothetical climate change next century is unlikely to spur much action. So clear-cut global warming in the next 1-3 years could provide a push needed to help move us toward the changes which will be required to bring down greenhouse gas emissions.

That brings me to my friendly wager. The conclusion about expected near term warming is based on simulations with a global climate model — the tool which has been thoroughly condemned as being unreliable — condemned by many scientists as well as bureaucrats. Also the statement I have made, that the world is getting warmer and that it is probably due to the greenhouse effect, has been widely criticized as being unjustified. If those criticisms are really believed, then surely someone would be willing to accept the following wager:

I claim that at least one year in the period 1990–1992 will be warmer than any year in the previous century. I win only if it is true in all of the main long term data sets: the GISS analysis of meteorological stations, the East Anglia analysis including ships, and Angell's upper air (radiosonde) data set. I get three years and you get 100 years. Someone mentioned that there will probably be an El Niño in the period 1990–1992. That may be so, but there were probably 20 or 30 El Niños in the previous century, including two very intense El Niños in the 1980s, which was the warmest decade. So there should be plenty of souls willing to make this wager. The offer remains open, so please contact me.

Can we learn anything about long term climate from temperature and other data for just the next three years? I think we can. If nature cooperates by holding off any large volcanoes, and if there is significant global warming consistent with the model calculations, it will improve our confidence in our understanding of the climate system's response to a sustained global forcing. On the other hand, if there is no warming or a cooling, it will suggest that we have overestimated climate sensitivity, overlooked other important climate forcings, or underestimated fluctuations in ocean transports.

ENDNOTES

1. Wonderland Model

The climate model used for the several hundred year simulation (Fig. 5) is a modification of the GISS model II. The physics is the same as in model II, except that the fundamental equations include a more accurate representation of the impact of water vapor on surface pressure and atmospheric thermodynamic properties, for the purpose of allowing simulations over a greater range of climate states. The primary difference compared to model II is the geography (Fig. 12), which, borrowing from an idea of Suki Manabe, covers only 120 degrees of longitude in the wonderland model, with cyclic repetition to fill out spherical geometry. The amount of land as a function of latitude is the same as in the real world, and the zonal mean climate simulated by the wonderland model is almost the same as for model II.

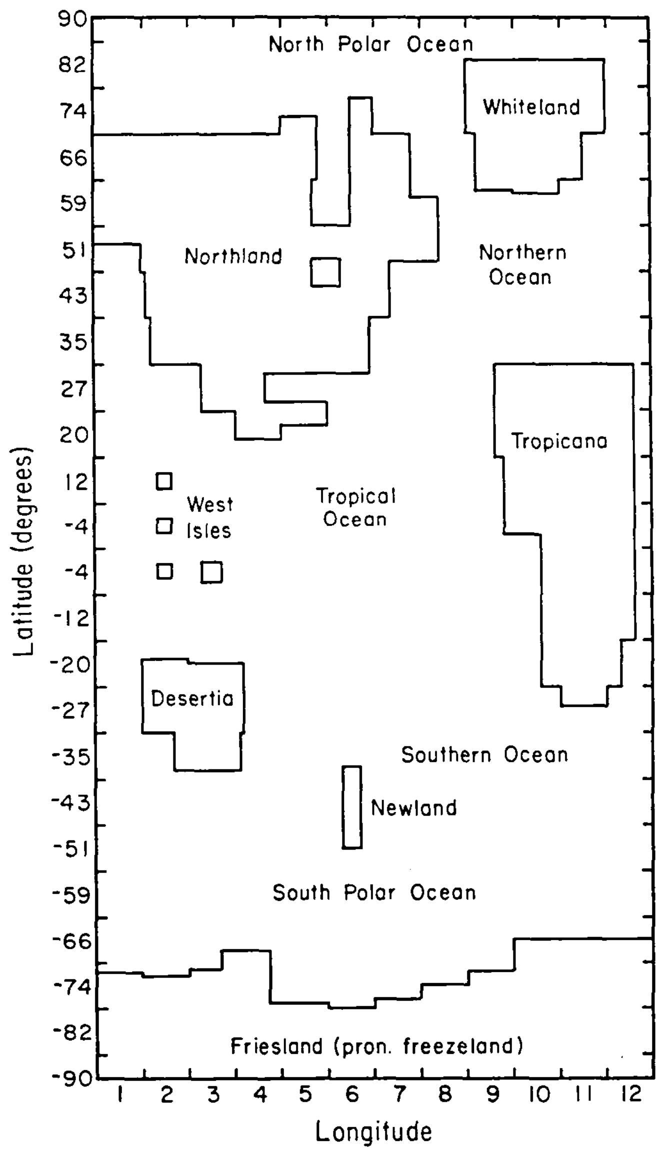

Fig. 12. Wonderland climate model.

The main advantage of the wonderland model is that it is three times faster than model II, thus allowing long simulations to be carried out on a computer of modest capabilities. A secondary advantage is the fictitious geography, which emphasizes the fact that the model is not the real world, thus helping the user focus on the climate processes simulated by the model.

2. *Rationale for a wager*

It has been pointed out to me that proposing a wager, especially since it was reported in a scientific journal (*Science* May 4, 1990), appears to be a bit unprofessional. On the other hand, it can be argued that it is worthwhile to draw attention to the issue of whether climate change during just the next few years has implications for longer term climate change.

However, the original rationale for the wager had a slightly different purpose. I concocted the proposed bet before the AGU meeting last December, under the impression that I would be in a panel discussion with Dick Lindzen. He has left the impression with the public that he disagrees with my assertion that the world is getting warmer and that the warming is probably due to the greenhouse effect; also, he argues that climate sensitivity is much less than indicated by the models and that the anthropogenic greenhouse warming may be small compared to natural variability. It seemed to me that given his position, he had to either accept the bet or do a fancy shindig which would undermine the extreme view credited to him. As it turned out, there was no panel discussion following our talks, so I had to save the proposition for the next conference. I had hoped that Bob Jastrow would bite on it, but he demurred on the grounds that the sun is increasingly warming the earth! That is interesting, since he has long argued that the Earth is already heading into an ice age. Also, the satellite data do not indicate a greater irradiance this solar cycle than in the previous one.

Wagers aside, it is interesting to look at data for the first few months of 1990. Preliminary numbers from our (Hansen and Lebedeff) analysis of surface air reports from meteorological stations show anomalies (relative to 1951–1980) of +0.5, +0.4, +1.5, +0.9C for the Northern Hemisphere and +0.1, −0.2, +0.2, +0.2C for the Southern Hemisphere for the first four months of 1990. The March anomaly is the largest for any month in our record, and, if the mean for the first four months held for the next eight months, 1990 would be the warmest year in our record. However, the largest anomalies almost always occur in Northern Hemisphere winter and early spring, and throughout the warm decade of the 1980s the first half of the year was considerably warmer than the second half. Thus, for 1990 to rank as the warmest year will require that the remaining months be substantially warmer than they were in the 1980s.

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