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A common-sense climate index: Is climate changing noticeably?

(global warming/greenhouse effect/carbon cycle)

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Contributed by James Hansen, February 6, 1998

ABSTRACT We propose an index of climate change based on practical climate indicators such as heating degree days and the frequency of intense precipitation. We find that in most regions the index is positive, the sense predicted to accompany global warming. In a few regions, especially in Asia and western North America, the index indicates that climate change should be apparent already, but in most places climate trends are too small to stand out above year-to-year variability. The climate index is strongly correlated with global surface temperature, which has increased as rapidly as projected by climate models in the 1980s. We argue that the global area with obvious climate change will increase notably in the next few years. But we show that the growth rate of greenhouse gas climate forcing has declined in recent years, and thus there is an opportunity to keep climate change in the 21st century less than "business-as-usual" scenarios.

Will Rogers, the American cowboy philosopher, once said, "It seems a scientist is a man that can find out anything, and nobody in the world has any way of proving he really found out anything or not" (1). Yes, scientists tend to speak in jargon. This tendency is a pernicious problem for an issue such as climate change, because ultimately the public, through its elected representatives, must decide on policies that will influence future climate. So it is desirable to find measures of climate change that are understood by a broad population.

Global warming has long been predicted to result from increasing greenhouse gases in the atmosphere (2–5). Global surface air temperature has indeed increased in the past century, but at a rate less than 0.1°C/decade (6–8). Record global temperatures have been achieved several times in the 1980s and 1990s, but a new record often exceeds the old record by only a few hundredths of a degree. What relevance, if any, do such small temperature changes have to most people?

A popular and important scientific activity is to develop techniques to "detect" (mathematically) significant climate change that can be associated with human-made climate forcings (9). A difficulty is that observed climate change is a result not only of natural and anthropogenic forcings, such as changes of solar irradiance and greenhouse gases, but also chaotic (unforced) variability of the climate system (10). Despite this, the Intergovernmental Panel on Climate Change (IPCC) reports probable detection of human-made climate change this century (9), and we have shown that the period of global satellite data contains clear climate imprints of both natural and human-made forcings (11). Our present paper does not concern scientific detection of human influence on climate, which we believe is already in hand.

But the practical detection issue is this: when will global warming be large enough to be obvious to most people? Until then, it may be difficult to achieve consensus on actions to limit climate change. It is common for people to perceive the latest climate fluctuation as long-term climate change. But it is just such misinterpretations that make it desirable to have quantitative measures of practical climate change.

In this paper we propose a climate index that is intended to provide an objective assessment of practical climate change. We also compare recent observed climate change with predictions made by climate models in the 1980s. Finally, we examine recent growth rates of greenhouse gases and discuss implications for future climate change.

Common-Sense Climate Index

Our climate index is a simple measure of the degree, if any, to which practical climate change is occurring. It also illustrates natural climate variability, thus revealing how difficult it is to reliably perceive a change of quantities that are naturally "noisy" or chaotic. Our aim is to help people judge whether or not climate fluctuations are a significant indication of change and to provide improved understanding of climate variability.

The index is a composite of climate quantities that are noticeable to the lay person. It is defined locally, because people experience local, not mean, conditions. The sense of the index is such that positive changes are expected with global warming, whereas negative values would occur with cooling. Thus the index is intended to be a measure not simply of whether climate change is occurring, but whether there is practically significant change of the nature predicted for global warming.

The index is derived from temperature and precipitation measurements. Temperature and precipitation are climate indicators noticed by people, and the sense of changes expected to accompany global warming are reasonably well defined. Also records of temperature and precipitation are often longer and probably have a better chance of revealing a detectable change than alternative climate variables such as cloud cover, winds, and humidity.

Our source of daily temperature and precipitation data is the National Weather Service Summary of the Day available from the National Climate Data Center (NCDC) for stations in the United States. Our source of monthly mean data is World Meteorological Organization Monthly Climatic Data of the World, also obtained from NCDC.

Data quality is an issue for all meteorological measurements, including temperature and precipitation (12). In a paper in preparation we define data quality checks in addition

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Abbreviation: CFC, chlorofluorocarbon.

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Table 1. Climate indicators in the temperature index

1. Seasonal mean temperatures (four seasons)
2. Degree days (heating season, cooling season)
3. Frequency of extreme temperatures (“hot” days, “cold” days)

to those inherent in the National Weather Service and Monthly Climatic Data of the World compilations. However, the climate changes required to yield a significant change of our climate index are so great that, where such changes are found on a large scale, they cannot be a consequence of measurement error.

Our index is inspired by and analogous to the United States Greenhouse Climate Response Index of Karl *et al.* (13). But the components of our index are different and we define a scale that is intended to make it obvious when a change is large enough to be noticeable to people. Also we use monthly Monthly Climatic Data of the World data to expand the index to the global scale.

The average value of the climate index is zero for the period of climatology, which we take as 1951–1980, a time when many of today’s adults grew up. The scale for the index is based on the interannual SD during this period:

$$\mathrm{SD} = \{\mathrm{Sum}_i\,[(T_i - T')^2]/30\}^{1/2},$$

where the sum is over the 30 years 1951–1980, T_i is an annual value (of temperature, for example) and T' is the 30-year mean.

The SD is a measure of the typical year-to-year fluctuation of the given quantity. A value +1 (or −1) is great enough to be noticeable, because a value that large or larger would normally (that is in the period 1951–1980) occur only about 15% of the time. For example, if the summer is warm enough to yield an index of +1 or greater at a given place, most people who had been living at that location for a long time would tend to agree that it was a “hot” summer.

Our contention that a persistent climate index of +1 or greater represents a noticeable climate change is presented as a hypothesis, because people’s perceptions are a sociological matter. But it is a testable hypothesis. We find that there are regions in Alaska and Siberia where the index is approaching unity, and thus surveys of people’s perceptions could be carried out.

The climate index occasionally will attain a value of +1 or more, even if no long-term climate change is occurring. But if such an index value is achieved and maintained, it will signify that substantial long-term climate change has occurred. Using the concept of climate dice (14), a persistent change of the climate index by +1 would represent a sufficient “loading” of the climate dice to be noticeable to most people. It may be noted that the SD would increase for a period longer than 30 years. But the change is slow, so keeping our unit of measure fixed for one or two decades has little effect.

Our composite climate index is the average of a temperature index and a moisture index. The components of these two indices are defined below. The climate index is available for hundreds of locations over the internet (www.giss.nasa.gov) as part of our “climate update.” We extend this data set annually.

Temperature Index. At locations in the United States, where the National Weather Service data include both daily and monthly temperatures, the temperature index is the mean of three climate indicators (Table 1). In the rest of the world, where Monthly Climatic Data of the World provides only monthly data, the temperature index is based on seasonal-mean temperatures. We find that, in places with both monthly and daily data (e.g., Fig. 1*D*), a high correlation between the index based on only seasonal temperatures and the index based on all three indicators.

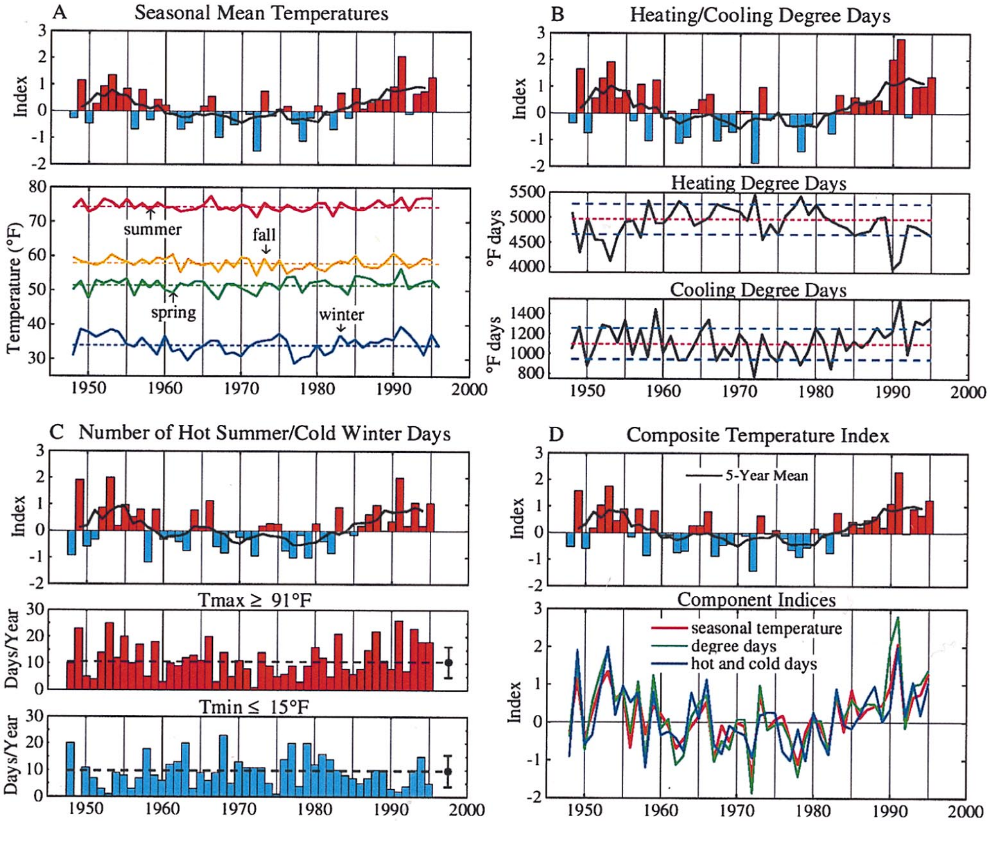

FIG. 1. Components of the temperature index for New York (La Guardia Airport), based on (*A*) seasonal mean temperatures, (*B*) heating and cooling degree days, and (*C*) frequency of unusually hot summer days and cold winter days. (*D*) The net temperature index. The lower part of each panel shows the input data for that index (see text).

As an example of the temperature index, we show results for New York (La Guardia Airport). Fig. 1*A* gives the mean temperature for each season. The component of the climate index based on seasonal-mean temperature is the mean of the indices for the four seasons. The largest index for seasonal temperature occurred in 1991. That year spring was remarkably warm on the United States East Coast, for example, cherry trees blossomed in early March in Washington, D.C. The unusual warmth was obvious to New York residents, as both the winter and spring were about 5°F above normal. But temperatures dropped back to normal the next year, in fact slightly below the 1951–1980 average.

Fig. 1*B* shows the second component of the temperature index, based on heating and cooling degree days. Heating degree days are calculated as the number of degrees that the daily mean temperature falls below 65°F accumulated over the entire heating season. Heating degree days less than normal give a positive contribution to the temperature index, whereas cooling degree days, based on temperatures above 65°F, give a positive contribution if they are greater than normal. In New York the largest values for the index associated with heating and cooling degree days occurred in 1990 and 1991, when it averaged more than two SDs above normal. The index has been high for the past decade, but not much higher than in the 1950s.

Fig. 1*C* shows the third component of the temperature index, based on the number of days when the temperature exceeds a level local inhabitants are likely to consider as "hot" or "cold." We define a hot day as one that occurred only 10 times per year, on the average, during the period 1951–1980, which yields 91°F or higher as the definition of a hot day in New York (and 15°F or less as a cold day). There were 26 "hot" days in New York in 1991, but in 1992 the number fell back to seven, i.e., less than the long-term mean. There is no obvious trend in the frequency of "hot" or "cold" days in New York during the past 50 years.

The composite temperature index for New York, the mean of the three components, is shown in Fig. 1*D*. The largest index occurred in 1991 with a value greater than 2. The unusual warmth of 1991 was obvious to the lay person, with record spring warmth, anomalies of more than 20% in heating and cooling degree days, a large number of hot days and few cold days. If such warmth continued, there is no doubt that most "baby boomers," who grew up during the period of climatology, 1951–1980, would agree on the existence of noticeable climate change. However, the temperature index fell back to near zero in 1992.

The decline of the temperature index in 1992 could be in part related to cooling caused by the 1991 Mount Pinatubo eruption, as the effect of stratospheric aerosols from that volcano maximized in 1992 (15). But the effect of such climate forcings are usually smaller than local unforced (chaotic) climate variability (11).

Moisture Index. The moisture index is the mean of three climate indicators (Table 2) at locations with both daily and monthly mean data. At locations where we use only monthly mean data, the moisture index is the mean of the first two indicators. We define the three indicators here and illustrate the resulting moisture index for New York City.

The components of the moisture index are based on data availability and expected effects of global warming. Climate models yield a 5–10% increase of global-mean precipitation for doubled CO_2, but precipitation does not increase everywhere (4, 9). Models yield some regions with decreased precipitation, mainly in the subtropics, but increased precipitation at most middle latitude regions and especially at high latitudes.

Table 2. Climate indicators in the moisture index

1. Seasonal total precipitation (four seasons).
2. Annual water deficiency.
3. Frequency of heavy precipitation.

We have emphasized in Congressional testimony[†] and in supporting scientific literature (16) that global warming should cause intensification of both extremes of the hydrologic cycle: droughts and forest fires, on the one hand, and heavy precipitation and floods, on the other. The simple reason is that, as climate patterns fluctuate, at times and places that are dry increased heating of the surface can only intensify drought conditions. But elsewhere, where water is available, increased heating increases evaporation, especially from warmer oceans, thus increasing precipitation. Our climate model (16) supports these expectations and also indicates that with global warming an increasing proportion of the precipitation occurs in deeper penetrating moist convection (thunderstorms) with a reduced proportion of rain occurring as large-scale super-saturation (wide-scale and thus more gentle soaking precipitation).

As an example of the moisture index, we again use results for New York. Fig. 2*A* shows the seasonal precipitation and the resulting component of the moisture index. There was a notable drought in the mid-1960s, and several sporadic wet years, but no evidence of long-term climate change.

Fig. 2*B* shows the annual water deficiency (17) for New York. A water deficit occurs when potential evapotranspiration (the evaporation that occurs if water is available on the surface) exceeds the sum of precipitation and available soil moisture (17). Water deficit is a measure of the stress affecting vegetation in the event of inadequate precipitation. Except at high latitudes, water deficiency is expected to increase with global warming (16), and thus we choose the sense of the index such that an increase of water deficit yields a positive climate index. Water deficiency is computed as a simple bookkeeping procedure, with precipitation as income, evapotranspiration as outgo, and 10 cm of soil moisture as a replenishable reserve drawn on as long as it lasts (17). We use Thornthwaite's (17) empirical formulation for potential evapotranspiration, which depends on monthly mean temperature. Trial calculations with daily data showed that, for the purpose of calculating interannual changes of water deficiency, monthly data yields a good approximation. Fig. 2*B* reveals a strong water deficiency in New York in the 1960s, but it does not suggest a long-term trend.

Fig. 2*C* shows the frequency of extreme precipitation in New York. Heavy precipitation is defined as that amount occurring on average five times per year in the period 1951–1980, which for New York implies a daily rainfall amount of 1.4 inches or more. Rare event precipitation is that amount occurring once every 5 years on average, which for New York implies a rainfall of 3.6 inches or more. Although these definitions of heavy and rare event precipitation are arbitrary, alternative choices had no noticeable effect on the index. The largest value of our extreme precipitation index for New York occurs in 1955, largely because there were two rainfalls exceeding 3.6 inches that year.

Fig. 2*D* is the net moisture index for New York. As expected, there tends to be a cancellation between the water deficiency and precipitation components of the moisture index for short-term climate fluctuations such as the drought of the mid-1960s. The moisture index is not designed to reveal short-term moisture fluctuations, but rather any possible long-term moisture tendency of the sense expected to occur with global warming. Climate models predict that both precipitation and water deficiency should tend to have long-term increases at most places, if the effects of global warming are predominate. But, as was the case for the temperature index, there is as yet no long-term change of the moisture index in New York that

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[†] Hansen, J., Testimony to U. S. Senate Committee on Commerce, Science, and Transportation, May 8, 1989.

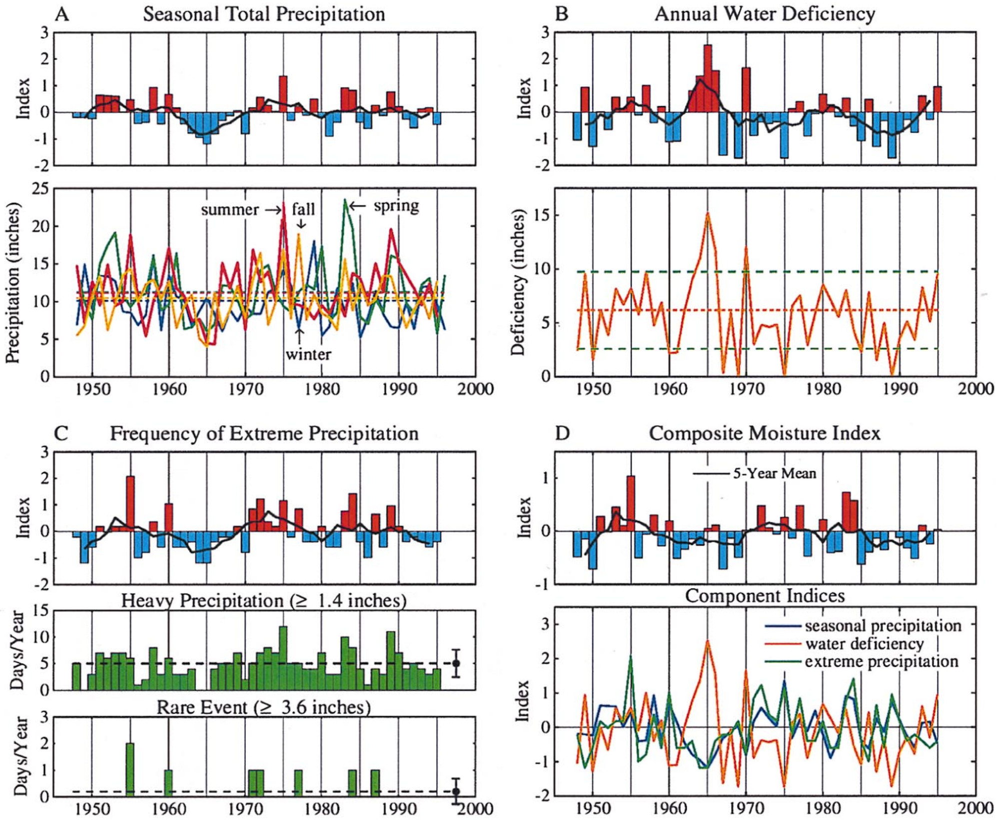

FIG. 2. Components of the moisture index for New York, based on (*A*) seasonal total precipitation, (*B*) annual water deficiency, and (*C*) frequency of extreme precipitation. (*D*) The net moisture index. Lower panels show the input data for each index component (see text).

would be obvious to most people. Specifically, the year-to-year fluctuations considerably exceed any long-term trend.

Climate Indices in the Region 30N–90N Latitude. Temperature and precipitation data are available for much of the Earth's land area. Because of the small spatial scale over which precipitation anomalies are representative and the limited station coverage in the tropics and Southern Hemisphere, we restrict our present analyses of the climate index to the region 30N–90N latitude. This area is also a region for which climate models predict reasonably coherent temperature and precipitation changes.

The spatial distribution of changes in the climate indices over the period 1951–1997 is shown in Fig. 3*A*, based on the local linear trends. Fig. 3*B*, for comparison, shows the global distribution of surface temperature change for the same period.

In most regions the climate indices are positive, the sense expected to accompany global warming, but the changes fall short of one local SD (the unit of measure). The moisture index is usually much smaller than the temperature index, a consequence of the large inherent variability of rainfall and thus of the moisture indicators. Therefore valid popular realization of long-term change of the moisture indicators is likely to be preceded by detection of temperature change.

Fig. 3 reveals areas in Asia and northwest North America (Alaska) where climate change might already be apparent to longtime residents. The temperature index is approaching unity (greater than 0.7) in 27% of the area with data, whereas it is less than −0.7 in only 4% of the area. The composite index exceeds 0.7 in 14% of the area and is less than −0.7 in 2% of the area. Fig. 3 also shows that the climate indices correlate strongly with surface temperature change. It is not surprising

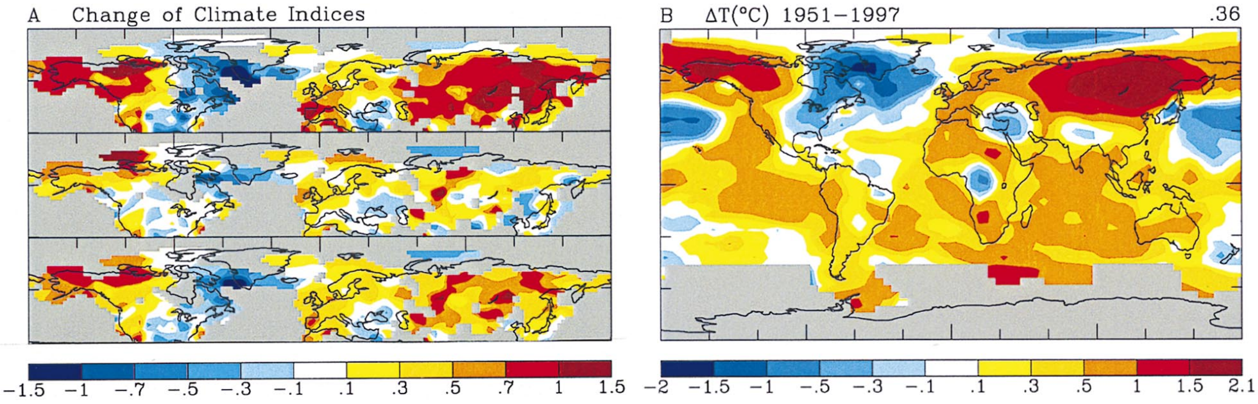

FIG. 3. (*A*) Change of climate indices (temperature, moisture and composite, from top to bottom) at latitudes 30N–90N based on linear trends for 1951–1997. (*B*) Global change of surface temperature for the same period, also based on local linear trends (8).

that the climate indices for New York have no obvious long-term change, because the temperature change there is nearly zero over the past five decades.

The map of observed temperature change since 1951 (Fig. 3*B*) serves as a reminder that even long-term climate changes are distributed very nonuniformly over the globe. We expect the fraction of the world where climate change is apparent, i.e., the areas with climate index of the order of unity, to increase in the near future, even in just the next several years (11). But the geographical distribution of the regions with obvious climate change may shift as a result of natural variability of climate patterns.

The global context of observed climate change (Fig. 3) is useful for another purpose. The geographical pattern, with the greatest change in remote Siberia, Canada and mid-ocean areas, debunks attempts to ascribe observed warming to urban effects on local thermometers. Other evidence, such as remote borehole data for subsurface temperature change and near global melt-back of alpine glaciers, also serves that purpose. But the global temperature change map (Fig. 3*B*) is a graphic proof that observed global climate change is not a figment of urban warming.

Can we anticipate future change of the climate index? We have found that the climate index is closely tied to global temperature, whose course is predicted by global models, which in turn are driven by presumed scenarios of greenhouse gases. Thus it is informative to examine the track records of climate models and greenhouse gas scenarios.

Climate Model Predictions

Expectations of climate change depend on global climate models. As actual climate unfolds we can keep a running comparison of observations with previous model predictions. These comparisons, as they lengthen, will help reveal model capabilities and deficiencies, thus aiding development of better models and improving understanding of climate change.

The relevant model predictions are "transient" experiments, in which the climate model is driven by time-dependent climate forcings, specifically atmospheric gases and aerosols that vary according to prescribed scenarios. The first transient calculations with a three-dimensional global climate model were carried out in 1987 (14), and thus there is now a 10-year record of observations for comparison with predictions. Climate change in this model were driven by observed and projected greenhouse gas changes and by aerosols from occasional volcanic eruptions.

Fig. 4 compares recent observed surface temperature with the simulations carried out a decade ago. The large interannual variability of even global mean temperature makes it difficult to draw inferences about model validity based on only a decade of observations. But, at least so far, the real world is behaving more like the model driven by scenarios B and C, rather than the model driven by scenario A.

Scenarios A, B, and C differ in assumed growth rates of greenhouse gases and in the presence or absence of large volcanic eruptions. Specifically, scenario A assumed that CO_2 and other trace gases would continue to increase exponentially at rates characteristic of the preceding 25 years, and it was assumed that there would be no very large volcanic eruptions. Scenario A was designed to reach the equivalent of doubled CO_2 by about 2030, consistent with the estimate of Ramanathan *et al.* (18).

Scenario B had a slower, approximately linear, growth rate of greenhouse gases, reaching the equivalent of doubled CO_2 at about 2060. Scenario B also included occasional cooling from large volcanic eruptions, specifically with eruptions in 1995 and 2015. Scenario C had the same volcanos as in scenario B but a still slower growth rate of greenhouse gases with a stabilization of greenhouse gas abundances after 2000.

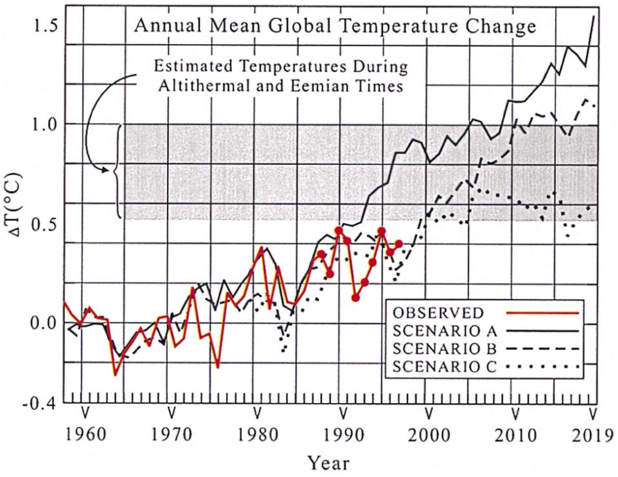

FIG. 4. Annual-mean global surface air temperatures computed by Hansen *et al.* (14). Observed global temperatures, including update of data subsequent to model predictions (dotted portion), are based on meteorological station measurements (6, 8).

One of our present "common sense" measures of climate change was explicitly predicted in our climate simulations 10 years ago: the frequency of unusually warm seasons (14). We calculated that on the average the chances of such seasonal-mean temperatures increased from about 30% in 1951–1980 to 50–70% in the 1990s (50–60% in scenarios B and C, 70% in scenario A), and we argued that this change is a sufficient loading of the climate "dice" that it may begin to be noticeable to people. Recently we plotted the observed frequency of such warm seasons (19). In the 1990s the frequency is about 50% globally and 50–60% at middle northern latitudes, in good agreement with the predictions for scenarios B and C (figure 6 of ref. 14).

These comparisons of observed and modeled temperatures raise the question of how actual climate forcings of the past 10 years compare with the scenarios used in the climate model. We show in the section below that the growth of greenhouse forcing in the real world has been close to that in scenario C (which, until year 2000, is not very different from scenario B). Real-world volcanos have been similar to scenarios B and C, with one large eruption in the 1990s, except that the actual eruption (Pinatubo) occurred in 1991 rather than 1995. Indeed, it is apparent in Fig. 4 that if the date of the volcano is altered accordingly, the model results for scenarios B and C fit the observations closely.

The record of observed climate change is too short to serve as a conclusive test of the model. But note in Fig. 4 that the observed and modeled global warming rates, with the realistic scenarios B and C, are consistent at 0.1–0.2°C/decade. This warming is about half of the rate that occurs in the "business-as usual" or equivalent 1% CO_2 per year scenarios used in some climate-change assessment studies (9).

The important point is that the rate of increase of climate forcings is falling short of the more extreme scenarios commonly used in climate simulations. Actual greenhouse gas climate forcings are quantified below.

Greenhouse Climate Forcings

A climate forcing is an imposed perturbation of the Earth's energy balance with space that tends to alter global temperature (20). Examples are a change in the solar radiation incident on the planet or a change in the amount of CO_2 in the Earth's atmosphere. The unit of measure is W/m^2, e.g., the forcing caused by the increase of atmospheric CO_2 since pre-industrial times is about 1.5 W/m^2. The total forcing caused by all anthropogenic greenhouse gases that have accumulated in the atmosphere is about 2.5 W/m^2 (9, 21).

Fig. 5*A* shows greenhouse climate forcing scenarios that were constructed in the 1980s and used in the climate predictions shown in Fig. 4. These scenarios can now be compared with "actual" forcings, i.e., with forcings calculated for measured changes of the primary changing greenhouse gases. These gases include CO_2, CH_4, N_2O, CFC-11, and CFC-12. The uncertainty in the forcing for these gases is less than 10% (20).

We show the greenhouse climate forcing with and without the ozone (O_3) contribution, because the O_3 forcing is less accurate than that of the other five gases. The uncertainty is because the changes of O_3 in the tropopause region, where it is most effective as a greenhouse gas, are not well measured. Estimates of O_3 forcing for the period 1979–1997 derived from O_3 measurements fall in the range -0.2 ± 0.1 W/m^2 (9, 20). [An alternative, less negative, estimate (22) based on observed temperatures is flawed by the fact that the tropospheric temperature profile would have adjusted over the period of measurement and was influenced by other climate forcings and feedbacks such as changes of water vapor and clouds. All of these factors are assumed to be fixed in the definition of a radiative forcing (20).] We use the value -0.2 W/m^2 here, which is in the middle of the estimated range.

Fig. 5*A* reveals that the "actual" greenhouse gas forcing falls near or just below scenario C. Our best estimate is between the "5 gas" and "6 gas" curves, because of the small warming that would be caused by all other trace gases. These other gases, mainly minor halocarbons, have been estimated to cause a forcing of about 0.005 W/m^2 per year in the 1980s (11).

The growth rate of greenhouse gas climate forcing is exposed more clearly in Fig. 5*B*, which shows the annual growth of the forcing. This figure uses the 5-year running mean of trace gas amounts to minimize the effect of high frequency noise in local measurements. For ozone we used the average rate of change in the period 1979–1995 to avoid even larger and more uncertain year-to-year variability.

The growth rate of greenhouse gas climate forcing peaked in the late 1970s, at about 0.04 W/m^2 per year, and has declined since then. The decline is dramatic when compared with "business-as-usual" scenarios, which assume continued growth of the annual increment of greenhouse gases.

Whence arises this change in the growth rate of greenhouse climate forcing? Fig. 6 reveals important changes in the growth trends of the three principal greenhouse gases.

The CO_2 growth rate increased rapidly until the late 1970s, more than doubling in 15 years (Fig. 6*A*). But the growth rate has been flat in the past 20 years, despite moderate continued growth of fossil fuel use and a widespread perception, albeit unquantified, that the rate of deforestation has also increased. Apparently the rate of uptake by CO_2 sinks, either the ocean, or, more likely, forests and soils, has increased. Although flattening of the CO_2 growth rate may be in part a figment of interannual and interdecadal variability, nevertheless, it emphasizes our ignorance of the factors controlling changes of the carbon cycle.

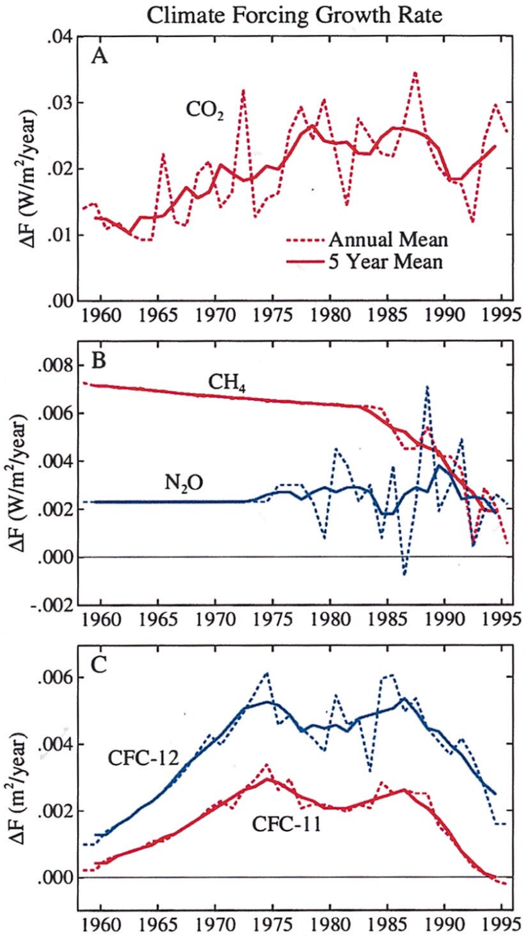

FIG. 6. Climate forcings by individual greenhouse gases: (*A*) CO_2, (*B*) CH_4 and N_2O, (*C*) CFC-11 and CFC-12, based on trace gas data available from the National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostics Laboratory (K. Masarie, personal communication). For 1958–1985, when annual CH_4 data are not available, we used a constant 15 ppb annual change estimated from ice core and other data (23).

One factor causing the overall growth rate of greenhouse forcing to decline is the recent plunge of the methane (CH_4) growth rate (Fig. 6*B*). The reasons for decreased CH_4 growth are uncertain. Sources of atmospheric CH_4 include wetlands,

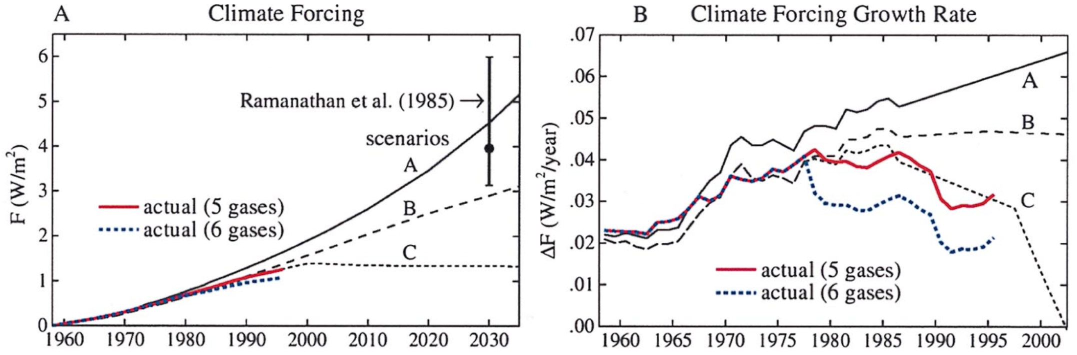

FIG. 5. (*A*) Climate forcing caused by greenhouse gas scenarios used in climate model predictions a decade ago (11) and (blue and red lines) "actual" forcings calculated from measured changes of the six principal greenhouse gases. (*B*) Annual change of greenhouse climate forcing, smoothed with 5-year running mean.

rice paddies, enteric fermentation and animal waste, fossil fuel production, landfills and biomass burning, while the principal removal mechanism is reaction with the hydroxyl radical (OH) in the troposphere (24). Several factors probably are involved in the slowdown of the CH_4 growth rate, including changes in the growth rate of the sources. It is noteworthy that the slowdown coincided with the period of ozone depletion. If ozone depletion increased the abundance of the tropospheric scavenger OH, and thus decreased the lifetime of CH_4, then the growth of CH_4 may increase as chlorofluorocarbons (CFCs) decrease and ozone recovers. But our ignorance of the balance of factors affecting CH_4 growth prevents reliable prediction of future trends.

Another factor causing the growth rate of greenhouse forcing to decline is a slowdown in the growth of CFCs (Fig. 6*C*). Production of the major CFCs is decreasing because of restrictions on their use imposed to protect the ozone layer (25). Thus their atmospheric abundances should decline gradually over the next century. The moderate negative term that CFC-11 and CFC-12 will contribute to the future change of greenhouse climate forcing, even though it may be balanced by increase of minor halocarbons, is a large change from the presumed growth of these gases in "business-as-usual" scenarios of the 1980s.

Review of all climate forcing mechanisms is beyond the scope of this paper. But evidence suggests that the dominant climate forcing on the century time scale is greenhouse gases (9, 21). Projection of greenhouse gas climate forcing devolves mainly into estimating CO_2 changes, because of the reduced growth of CFCs and CH_4. A useful guide to the future is provided by recent growth rates (Fig. 7*A*).

The CO_2 growth rate is a function of fossil fuel use, but also of the deforestation rate and uptake of CO_2 by the oceans, soil and forest regrowth. A convenient measure of effects other than fossil fuel emissions (shown in Fig. 7*B*) is the "airborne fraction," which is the ratio of the amount of CO_2 accumulating in the atmosphere to the amount emitted by burning of fossil fuels and cement production (T. Boden, personal communication). Fig. 7*B* shows that, averaged over a few years, the airborne fraction has remained close to 0.6 over the past 40 years.

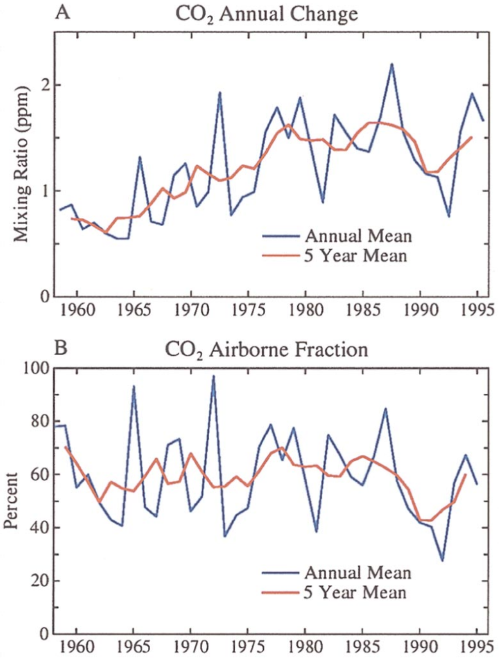

FIG. 7. (*A*) Annual atmospheric CO_2 increase. (*B*) Ratio of observed CO_2 increase to industrial emissions.

We estimate future CO_2 changes as an extension of recent growth rates with different scenarios for fossil fuel use in developed and developing countries. We replace uncertainties of carbon cycle models with an assumption that the airborne fraction will continue to be approximately 0.6. We take the recent CO_2 growth rate as 1.6 ppm per year, associate two-thirds of this with developed countries and one-third with developing countries.

We define scenarios dubbed (A) fast growth, (B) moderate growth, and (C) slow growth (Fig. 8). Fast growth assumes that the developing world will maintain an exponential 3% per year emission growth rate for the next century, similar to the rate that the developed world maintained in the past century. Because this scenario would deplete oil and gas reserves it implicitly assumes that coal and perhaps nontraditional fossil fuels such as shale oil and tar sands will assume an increasing proportion of energy use. Fast growth also assumes that the developed world will maintain 1% per year growth rates for the next century, similar to growth in the United States in the 1990s.

Moderate growth assumes that the developing world will maintain exponential 2% per year growth of emissions for the next century, and the developed world will average 0% growth in emissions. Slow growth assumes that the annual increment of airborne CO_2 will average 1.6 ppm until 2025, after which it will decline linearly to zero in 2100.

Comparable assumptions are made for the minor greenhouse gases (Table 3). These have little effect on the results.

Several conclusions follow from Fig. 8. Climate forcing by greenhouse gases in the real world has been falling far short of the "1% CO_2" transient scenario, which is an idealized greenhouse gas scenario sometimes used for transient climate change studies (9). Indeed, the actual greenhouse forcing is only about half of that for "1% CO_2." Thus greenhouse "skeptics" who claim to disprove climate models by searching for and failing to find the 0.3°C per decade warming obtained by models with 1% CO_2 growth are raising a "red herring." In fact, as shown by Fig. 4, climate models driven by observed greenhouse gas changes yield a warming rate in accord with observations.

The main conclusion we draw from Fig. 8 is an optimistic one. The slowdown of greenhouse climate forcing growth rates suggests that there is an opportunity to avoid the more rapid rates of climate change in the 21st century. Even the equivalent of doubled CO_2 climate forcing (4.2 W/m^2) is not inevitable.

Certainly it is conceivable for developing countries to maintain 3% annual growth of CO_2 emissions for a century, should they strap economic growth tightly to increased fossil fuel use, and for the developed world to maintain 1% annual growth for a century, should they mimic economic growth and fuel use trends of the United States in the 1990s. But common sense suggests that reasonable attention to climatic consequences,

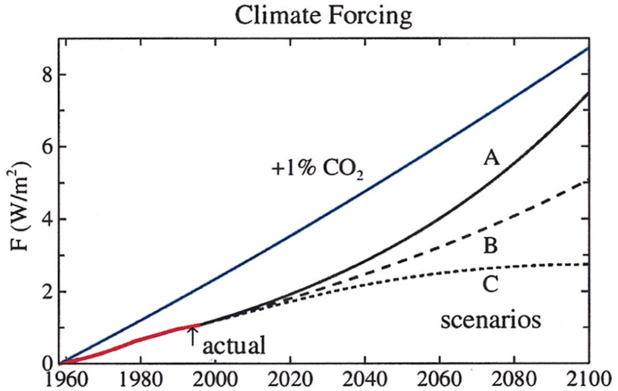

FIG. 8. Climate forcing scenarios (see Table 3).

Table 3. Greenhouse gas scenarios, annual growth rates

Scenario	CH_4	N_2O	CFCs	ΔCO_2
A	0.5%	0.25%	0	3% developing 1% developed
B	0.25%	0.25%	0	2% developing 0% developed
C	0%	0.25% at 2025 to 0% at 2100	0	1.6 ppm/yr to 2025 to 0 ppm/yr at 2100

along with technological developments in energy efficiency and alternative energy sources, will render scenario A undesirable and improbable.

A more prudent and likely near-term course is in the range of scenarios B and C, which yield an added greenhouse forcing of 1 W/m^2 in 30–40 years. Although the range of practical policy options is unlikely to affect CO_2 growth much in the next few decades, small changes in the trends become important later in the century. This is the compounding effect of small continuous changes, illustrated by the large differences that develop among scenarios A, B, and C. Moreover, if a slowdown of CO_2 emissions is achieved via a common-sense emphasis on energy efficiency and development of alternative clean energy sources, it will provide an increased range of future policy options as the climatic and economic consequences become clearer.

Summary

Climate Index. At most places in the world the climate index, a composite of climate indicators noticed by people, has changed in the sense expected for global warming. In certain areas, mainly in Asia and Alaska, the index has reached a value such that the climate change should be apparent to local residents. If global warming proceeds according to our climate model projections, there should be a large increase of the area with obvious climate change during the next several years.

Climate Models. It has been one decade since the first climate predictions were made by using time-varying greenhouse gases in a global climate model. Subsequent observations and the model are in good agreement for the case in which the model is forced by greenhouse gas growth rates close to observations. Predicted change in the frequency of unusually warm seasons, a climate indicator noticeable to people, also has proven to be accurate.

Climate Forcings. The growth rate of the net greenhouse gas climate forcing reached a peak of about 0.4 W/decade in the late 1970s and has declined moderately since then. The decline in the net forcing is because of a leveling off of the growth of CO_2 climate forcing and declining growth rates of CH_4 and CFCs.

Plausible projections of greenhouse gas growth rates suggest that the equivalent of doubled CO_2 greenhouse climate forcing is not inevitable. Such a large climate forcing is possible if developing countries follow an exponential growth curve of CO_2 emissions, similar to the history in developed countries, and if the developed world continues to increase its greenhouse gas emissions. On the other hand, if the economic development in the developing world includes increased energy efficiency and increasing use of nonfossil fuel energy sources, and if developed countries stabilize and reduce their CO_2 emissions, the future climate forcings and climate change may be much more moderate than in "business as usual" scenarios.

The Missing Climate Data. The large changes in climate forcing trends in just the past 1–2 decades emphasize the difficulty of long-term climate projections and our ignorance of many issues that influence predictions for the 21st century. For example, why has the CO_2 growth rate leveled out in the past two decades, despite increased emissions and deforestation? Might the implied missing CO_2 sink(s) begin to "fill up" or even become future CO_2 sources, or will the sinks grow as airborne CO_2 increases? Why has the growth rate of methane plummeted? Will it accelerate again, or is it possible that we could take steps to make its growth negative, thus balancing some of the CO_2 warming? What are aerosol direct and indirect climate forcings and how are they changing?

Despite the emergence of climate change as a topic of global strategic importance, support for the fundamental research needed to develop quantitative understanding of such issues has not increased markedly, especially for university research. Perhaps there is a feeling that stressing knowledge gaps will be detrimental to environmental conservation efforts, or that calls for research support appear to be a case of "feathering one's own nest." But without improved support of fundamental research we cannot reliably predict future changes of climate forcings and climate itself, and thus it will be impossible to assess accurately the effectiveness of policy options.

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1. Utah newspaper, August, 1989 (quotation of the day, original source: Weekly Articles, 1929, Will Rogers Memorial, Claremore, OK).
2. Arrhenius, S. (1896) *Philos. Mag.* **41,** 237–276.
3. Callendar, G. S. (1938) *Q. J. R. Meteorol. Soc.* **64,** 223–240.
4. Manabe, S. & Wetherald, R. (1975) *J. Atmos. Sci.* **32,** 3–15.
5. Hansen, J., Johnson, D., Lacis, A., Lebedeff, S., Lee, P., Rind, D. & Russell, G. (1981) *Science* **213,** 957–966.
6. Hansen, J. & Lebedeff, S. (1987) *J. Geophys. Res.* **92,** 13345–13372.
7. Jones, P. D. (1994) *J. Clim.* **7,** 1794–1802.
8. Hansen, J., Ruedy, R., Sato, M. & Reynolds, R. (1996) *Geophys. Res. Lett.* **23,** 1665–1668.
9. Intergovernmental Panel on Climate Change (1996) *Climate Change 1995*, eds. Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A. & Maskell, K. (Cambridge Univ. Press, Cambridge, U.K.).
10. Lorenz, E. N. (1984) *Tellus* **36,** 98–110.
11. Hansen, J., Sato, M., Ruedy, R., Lacis, A., Asamoah, K., Beckford, K., Borenstein, S., Brown, E., Cairns, B., Carlson, B., *et al.* (1997) *J. Geophys. Res.* **102,** 25679–25720.
12. Karl, T. R., Tarpley, J. D., Quayle, R. G., Diaz, H., Robinson, D. A. & Bradley, R. S. (1989) *Rev. Geophys.* **27,** 405–430.
13. Karl, T. R., Knight, R. W., Easterling, D. R. & Quayle, R. G. (1996) *Bull. Am. Meteorol. Soc.* **77,** 279–292.
14. Hansen, J., Fung, I., Lacis, A., Rind, D., Lebedeff, S., Ruedy, R., Russell, G. & Stone, P. (1988) *J. Geophys. Res.* **93,** 9341–9364.
15. Hansen, J., Lacis, A., Ruedy, R. & Sato, M. (1992) *Geophys. Res. Lett.* **19,** 215–218.
16. Hansen, J., Rind, D., DelGenio, A., Lacis, A., Ruedy, R. & Karl, T. (1991) in *Greenhouse-Gas-Induced Climatic Change*, ed. Schlesinger, M. E. (Elsevier, Amsterdam), pp. 211–229.
17. Thornthwaite, C. W. (1948) *Geogr. Rev.* **38,** 55–95.
18. Ramanathan, V., Cicerone, R. J., Singh, H. B. & Kiehl, J. T. (1985) *J. Geophys. Res.* **90,** 5547–5566.
19. Hansen, J. (1997) in *Carl Sagan's Universe*, eds. Terzian, Y. & Bilson, E. (Cambridge Univ. Press, Cambridge, U.K.), 282 pp.
20. Hansen, J., Sato, M. & Ruedy, R. (1997) *J. Geophys. Res.* **102,** 6831–6864.
21. Hansen, J., Sato, M., Lacis, A. & Ruedy, R. (1997) *Philos. Trans. R. Soc. London B* **352,** 231–240.
22. Zhong, W., Toumi, R. & Haigh, J. D. (1996) *Geophys. Res. Lett.* **23,** 3183–3186.
23. Ehhalt, D. H. in *The Changing Atmosphere*, eds. Rowland, F. S. & Isaksen, I. S. (Wiley, New York), pp. 25–32.
24. Crutzen, P. J. (1991) *Nature (London)* **350,** 380–381.
25. Prather, M., Midgley, P., Rowland, F. S. & Stolarski, R. (1996) *Nature (London)* **381,** 551–554.