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The Challenge of Identifying Greenhouse Gas–Induced Climatic Change

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Introduction

Observations and diagnostic studies clearly indicate that the atmospheric concentrations of CO_2 and other trace gases have been rising steadily as a consequence of human activities. Laboratory experiments demonstrate that these increased concentrations will enhance the infrared absorptive capacity of the atmosphere, thereby intensifying the natural greenhouse effect that sustains the earth's climate well above freezing. Theoretical calculations suggest that the enhanced greenhouse effect since the 18th century should have measurably warmed the global climate, and indeed some warming has apparently occurred. Some environmentalists are suggesting that these results alone require that societal activities be substantially altered to prevent further climatic change. Critics may agree to cost-effective actions that also serve other purposes, but argue that the theoretical projections must be observationally confirmed before drastic steps are taken. This confirmation that greenhouse gas emissions are indeed causing significant climatic change has become a critical research challenge.

Successfully meeting this challenge is critical for several reasons. First, it would provide an affirmation of scientific understanding of the climate system, confirming that its behavior can be projected, at least within some limits to be identified. Second, being able to confirm that the enhanced greenhouse effect is occurring on a global scale will help in reducing uncertainties (i.e., constraining the range of possibilities suggested by models) and in enriching our understanding about how climate changes may be evidenced on a regional scale. Third, being able to say with high statistical confidence that the initial stages of the changes have been identified and attributed to greenhouse gases will provide an incentive for enhanced efforts to improve understanding of potential impacts on societal resources and public and political appreciation of the need to consider societal responses to limit or adapt to future changes in climate.[1]

Meeting the challenge of identifying greenhouse gas-induced climatic change involves three steps. First, observations of critical variables must be assembled, evaluated, and analyzed to determine that there has been a statistically significant change. Second, reliable theoretical (model) calculations must be conducted to provide a definitive set of changes for which to search. Third, a quantitative and statistically significant association must be made between the projected and observed changes to exclude the possibility that the changes are due to natural variability or other factors. This paper provides a qualitative overview of scientific progress in successfully fulfilling these three steps.

Selecting Climatic Measures

Climate is a term that encompasses the mean and the higher statistical moments of all measures of the state of the atmosphere, the oceans, the cryosphere, and, in its broadest sense, at least some descriptors of the biosphere. For a number of reasons, the search for changes has been and must be narrowed to a limited set of variables.

Of primary importance, accurate observational records of the climatic parameters need to exist over a long enough time to determine whether a change has occurred. This requirement is not easily satisfied. First, the observations must be taken with sufficient precision that real changes can be distinguished from ones due to changes in instruments, in measurement protocol (e.g., time of day of measurement), and in or around the measurement location (e.g., station moves, urbanization, desertification, irrigation). Although there are a number of approaches to adjusting the observational record to account for such shortcomings, experience indicates that, because most observations are taken to aid in weather prediction rather than to document climatic change, the "corrections" are often nearly as large or larger than the greenhouse signal to be identified.

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[1] It should be noted that detection of change will likely mean that an independent mathematician would be convinced that the present climate is different than that for some period in the 19th century, and not that a recent or sudden change has occurred, as so often seems to be implied by press accounts. Given the large range of paleoclimatic changes, being able to totally rule out natural variations as a cause may not be possible.

Second, the length of the record must be sufficiently complete (i.e., without long gaps) and long enough that the long-term changes associated with the changing greenhouse gas concentrations can be distinguished from fluctuations due to other factors. Natural fluctuations and variations can occur on scales from seasonal to interannual to decadal and longer and can result from inherent natural variability (e.g., atmosphere-ocean coupling) and radiative forcings other than those due to changes in greenhouse gas concentrations (e.g., volcanic activity, solar variability). Because the forcing-response patterns of these nongreenhouse variations are poorly understood, the requirement to have a long record is reinforced because of the need to establish a baseline climate to which to reference the greenhouse-induced change. Because the concentration changes (and presumably the induced climatic changes) have been occurring for more than 200 years and because climatic observations go back only about 100 years, even the longest sets of observations available allow examination only of trends (or changes in trends). These limits on the length of the record thus complicate identification of the greenhouse signal. (There are proxy or reconstructed records that extend further into the past, but these measures are less accurate due to the assumptions and transfer techniques that must be used to make them equivalent to presently observed climatic parameters.)

Because the temporal variability of the climate increases as the spatial scale decreases, having records of climatic variables over large areas allows averaging that tends to reduce the variability and more clearly shows the smaller, longer-term changes in climate. It is thus desirable to have records that can be used to generate hemispheric or global averages. This requirement, however, conflicts with the earlier requirements because spatial coverage generally decreases for older records (particularly over ocean areas and in the Southern Hemisphere). Ensuring consistency of instrument usage and the need to average records of different stations also can introduce difficulties. These difficulties include uneven spacing of stations, the differing baseline conditions at different stations (a factor that usually leads to averaging of deviations from a baseline value rather than averaging of the observations themselves), differing durations of the records at different stations, and different types of instruments and measurements in different regions (land vs. ocean, one country vs. another, etc.).

Given these many complications, the set of variables that might be analyzed to seek greenhouse gas–induced climatic change is not large. Table 1 lists parameters that might be analyzed. The entries are separated into those for which reasonable records exist and

Table 1: Parameters expected to be changed by greenhouse gas-induced climatic change

Parameters for which useful records exist

- Near-surface air temperature
- Sea surface temperature
- Stratospheric temperature
- Precipitation over land
- Sea ice extent
- Sea level

Parameters for which limited areal or temporal records currently exist

- Tropospheric temperature
- Upper ocean temperature*
- Subsurface temperature (e.g., in permafrost)
- Atmospheric water vapor
- Snow cover/mountain glacier extent
- Ocean circulation/salinity
- Atmospheric chemistry
- Ecological systems (extent and character)

*Over the next decade, a new acoustic measurement technique may elevate this parameter to the first category because the noise level of the technique is quite low.

those for which records may be developed in the future, but for which there are now overriding limitations in the areal extent of the measurements or the length and consistency of the record.

For those measures for which there is an extended record, there remains a range of problems in attempting to determine trends. None of the records is long enough to provide a baseline climate before greenhouse gas concentrations started to increase. Most statistical techniques assume the individual (e.g., annual) data points are independent and/or normally distributed, neither of which is true for climatic data; as a consequence, such techniques must be applied with caution. The limited length of the record, low-frequency variability, and changing spatial coverage of the measurements further complicate the analysis (Wigley et al., 1985).

Although the discussion here will cover only those parameters for which extended records now exist, there is great expectation that new techniques will make additional records available over the next decade. For example, Spencer and Christy (1990) are using satellite microwave radiance data to derive a precise, low-noise measure of midlevel tropospheric temperatures, and Munk (Gibbons, 1990) proposes to use acoustic signals to provide a temperature record of similar quality for the upper ocean. Permafrost temperature records will also become more abundant as measurements are made in the Eurasian Arctic.

At present, however, the set of measures now available to use in seeking to identify greenhouse gas-induced climatic change is rather limited, consisting mainly of temperature, sea ice, and sea level. In addition, none of the records goes back in time before the start of significant increases in the concentration of greenhouse gases; as a result, we have no truly independent and highly resolved record of the natural variability of the climate.

Theoretical Estimates of Climatic Change

The concentrations of greenhouse gases have been increasing since the mid-1700s, with the CO_2 concentration having increased about 25% and the CH_4 concentration having more than doubled (Watson et al., 1990). These changes would imply that the climate has therefore been changing due to these emissions for more than 200 years, albeit at first quite slowly. If we are to be able to associate past changes in climate with these increasing concentrations, we must have available theoretical estimates of what the induced changes in climate were. Although climate models have been improving over their 30-year history, there has not yet been even one globally resolved model calculation attempting to simulate the last 200 years. There have been very few calculations attempting to realistically simulate the last 30 years (Hansen et al., 1988). That model had a simplified ocean and did not represent the residual effects of concentration changes earlier than its starting date of 1958, even though Hansen et al. (1988) estimate that the e-folding time of the oceanic response was of the order of 100 years.

Given the requirement for a theoretical estimate of the change to demonstrate identification (or detection), the lack of such an estimate obviously prevents attainment of the objective, at least without approximation. This failure to conduct the required simulation arises not primarily because of limitations in computer resources (although this is an important constraint). First, we do not have information about initial oceanic conditions, and about volcanic eruptions, solar variability, and other natural climate-forcing factors that would also be affecting the climate. Second, we do not yet have adequately verified, coupled atmosphere-ocean models capable of such simulations. Third, any such simulation experiment must be made in recognition of the confounding influence of natural variability, which is not yet either adequately understood or properly treated in the models. As a consequence, we are quite far from having the necessary model simulation(s) to permit accurate estimation of greenhouse gas–induced climatic change.

To sidestep this lack of the proper simulation, estimates of the greenhouse gas–induced climatic changes are commonly used, even though there are many simplifications and pitfalls involved in developing these approximations. The preferred technique for deriving estimates of the climatic change expected over the industrial period is to interpolate between equilibrium simulations of one and two times the 1950 (or thereabouts) concentration of CO_2, using the radiative forcing at the tropopause from the increasing concentrations of CO_2 and other trace gases as the interpolant. Account must also be taken of the role of the oceans in diminishing or postponing some fraction of the scaled equilibrium change, which requires that we understand how the oceans work. Modeling studies indicate that the instantaneous climatic effect may be reduced by 20–50% and that the oceanic response time may be from a few decades to much more than a century. Paleoclimatic studies suggest that the entire oceanic circulation can respond, which would further complicate the estimation of the expected change.

In addition to the uncertainties introduced because of limitations of and differences among models (which are extensive; see Grotch and MacCracken, 1991), this interpolative approach assumes that equivalent global radiative forcing by CO_2 and other trace gases will have the same climatic effect (see, however, Wang et al., in press, which suggests this may not be the case), that equilibrium climatic changes will look like time-dependent changes, and that climatic change is linear in radiative forcing. Each of these assumptions is known to be at least slightly incorrect. Different trace gases have different latitudinal and altitudinal effects on radiation. Model simulations of transient changes (e.g., Schneider and Thompson, 1981; the most recent general circulation model results are reviewed in Bretherton et al., 1990) indicate that changes are not equally proportional at all locations, and clearly the large temperature changes associated with the meltback of Arctic ice are not equal in all seasons, but occur initially in the transition seasons rather than in winter as doubled CO_2 simulations would suggest. Lorenz (1984) has pointed out that the climate may not be transitive; that is, the climate may have more than one stable state. As a consequence, it is conceivable that the climate may not change gradually, but rather may jump from one state to another, thereby nullifying the linear assumption. (The relatively rapid warmings centered around 1920 and 1980 would seem to support this proposition.) Theoretical calculations (Wigley and Schlesinger, 1985) also suggest that the climatic change at any time is dependent on the rate of change of forcing and the ultimate equilibrium change, thereby moderating the linear approximation. As other examples of nonlinearity, precipitation patterns shift (causing wetter and drier changes that cannot be linearly approximated), mountain glaciers eventually completely disappear, and sea level increase has a very long time constant because of the time for heat uptake in the deep ocean.

Brushing aside all of these approximations and uncertainties (and more), radiative model calculations (Shine et al., 1990) suggest that the greenhouse forcing at the tropopause has been 2.45 W/m^2 since 1765 (about 1.92 W/m^2 since 1900) in comparison to the 4.4 W/m^2 usually associated with a CO_2 doubling. If temperature changes are linear in forcing and the climatic sensitivity to a CO_2 doubling is 1.5 to 4.5°C, then, before accounting for ocean lag, the expected equilibrium temperature change since 1750 is about 0.8 to 2.5°C (about 0.65 to 1.95°C since 1900). Although not valid on a local basis, the realized temperature changes (i.e., estimates for which the effect of the ocean thermal inertia has been accounted) are about 50 to 80% of these equilibrium changes. Based on these techniques (invalid as they may be), temperature changes from 1765 to the present are expected to be about 0.4 to 2.0°C (0.35 to 1.6°C since 1900). If we also assume that the latitudinal pattern of the changes will be consistent with the equilibrium changes (probably a poor assumption, as indicated above), the present temperature changes are expected to be about twice the global average at high latitudes and one-third to one-half the global average at low latitudes.

Stratospheric temperatures at about 25 km, for which there would be somewhat less effect of the oceanic lag,[2] would be expected to have dropped about 2°C since 1765 and about 1°C since 1960, when a reasonably representative array of observations started to become available. Interpolation would suggest that global precipitation should have increased several percent, especially in high latitudes, although the high interannual and spatial variability would make these changes very difficult to identify (Bradley et al., 1987). Sea ice should have melted back, although models do not include processes such as sea ice advection that may obscure or compensate the meltback. Models of sea level increase are relatively limited, emphasizing the component due to thermal expansion, but not adequately treating changes in mountain glaciers or in the polar icecaps. Simplified ocean models suggest that a rise in sea level of 0.1 to 0.2 m might be expected based on predicted climatic changes of the last 150 years, but no comprehensive calculation has been done that treats all factors (and calibrated simulations with simplified models do not provide an independent check).

Thus, even allowing for approximations, the set of parameters that are expected to have changed in a manner that is detectable is

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[2] Although the radiative time constant is short, stratospheric temperature changes will also depend on the tropospheric temperature change, which is delayed.

quite sparse and so uncertain that achieving definitive identification of the greenhouse signal is quite problematical.

Has the Climate Changed as Expected?

Not only are the observational data sets and the model estimates limited, but additional problems arise in attempting to associate changes with the increasing concentrations of greenhouse gases in a quantitative manner. The primary difficulty is that the climate has varied on many different time and space scales due to many factors in addition to changes in the concentrations of greenhouse gases. Examples of factors generally considered external to the climate system include volcanic eruptions and solar variations, although it appears that the flux changes caused by such factors are less than for trace gases (Hansen and Lacis, 1990). Paleoclimatic records suggest that, in addition to responding to cyclic variations in the earth's orbit and to changes in atmospheric composition, the climate has varied, even on relatively short time scales (decadal to centennial), by substantial amounts solely as the result of internal variability. These internal variations are also apparent in the historical record (the Medieval Warm Period, ca. A.D. 1100–1250, was probably somewhat warmer than present, and the Little Ice Age, ca. A.D. 1450–1850, somewhat cooler) and in year-to-year climate variations. Thus, in evaluating whether the climate has changed, the role of other factors in inducing climatic change must also be distinguished from the greenhouse gas–induced effects, even though we are even less certain of the types of climatic change that these other factors may have induced.

In spite of all of these limitations, it is nonetheless interesting to evaluate how well the observed changes in climate match the theoretically calculated changes. Changes in near-surface air temperature have been considered most often. (Changes in sea surface temperature give quite similar results.)

Figure 1 displays the estimates of Northern Hemisphere, Southern Hemisphere, and global changes in near-surface air temperature compiled by Jones et al. (1991) from land and marine records. Comparable data sets have been assembled by Hansen and Lebedeff (1988) and by Vinnikov et al. (1990), each making different adjustments to assure homogeneity and representativeness of the records. Problems remain with each set, particularly concerning spatial coverage and urbanization around stations, but these are steadily being reduced.

The records show significant year-to-year variability, especially in the 19th century, probably an artifact of the more limited spatial coverage of the observations. Although there is a general increase in

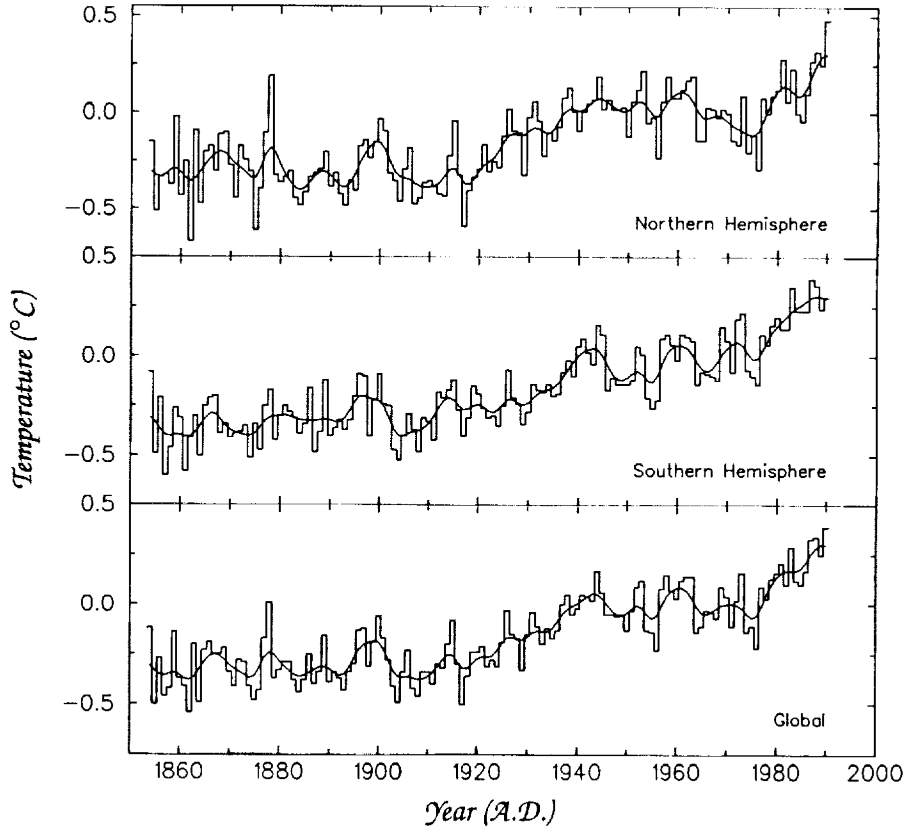

Figure 1. Area-weighted estimates of annual temperature departures from a reference normal for the Northern Hemisphere, Southern Hemisphere, and global land and ocean areas for the period since 1860 (Jones et al., 1991).

the temperature, the increase is less steady in the Northern than in the Southern Hemisphere, with a rapid rise in the early 20th century followed by a period of slight cooling from 1940 to the 1970s followed by a rapid rise. This uneven pattern of rise is most evident in the Northern Hemisphere land record, which is often cited as evidence that recent changes in climate are due at least in part to factors other than the greenhouse effect (e.g., natural variability, sulfate aerosols).

It is also important to understand that these curves are composited from values at many individual points. Although the year-to-year variation of the global mean is only about 0.5°C, the standard deviation of the set of individual grid-point values about the global average value was about 0.75–1°C prior to 1940, then decreasing to about 0.5°C (Grotch, 1987). Figure 2 presents a three-dimensional histogram of the distributions of individual grid-point values for

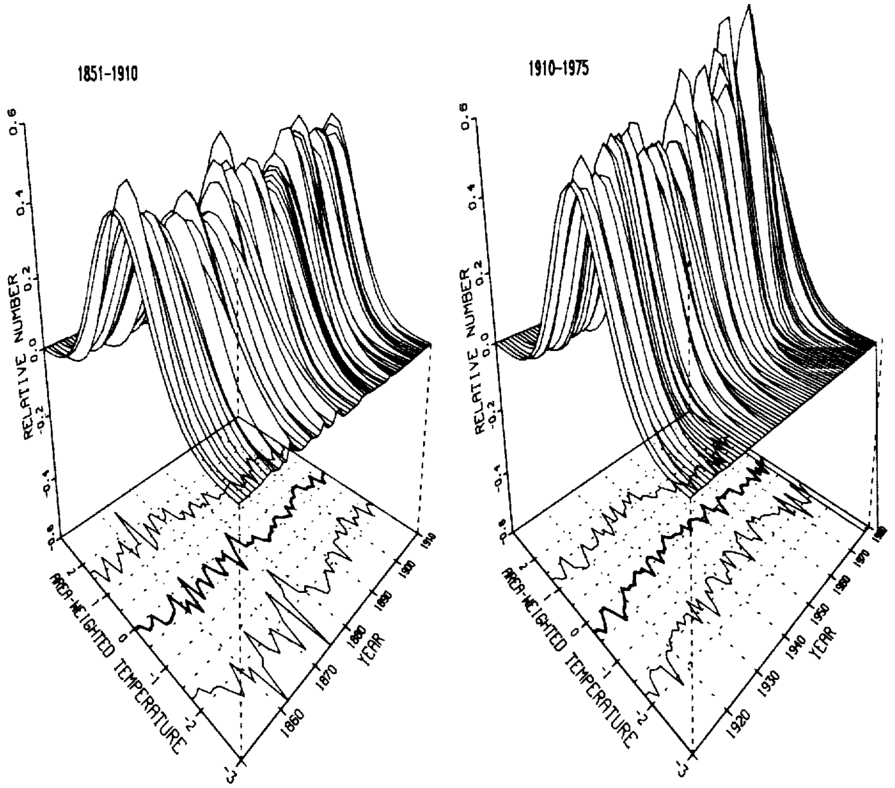

Figure 2. Three-dimensional histogram of the distribution of area-weighted temperature anomaly over time (CRU data 1850–1976). The values for each year are assumed to be normally distributed. On the lower surface, the estimated average anomaly is drawn as a heavy solid line and the ±2σ estimates are shown as lighter lines (Grotch, 1987).

each year of the record, illustrating that the changes in the mean are well within the bounds of past variations; that is, although the mean is increasing, particular locations can have quite different annual anomalies than the global mean. Grotch (1989) has shown that the correlation between changes at individual grid points and the global (or hemispheric) average value is positive, but low. Thus, it is interesting, but not surprising, that particular regions show patterns that are different than the global average. For example, the U.S. Historical Climate Network shows a relatively steady average temperature over the period of record (nighttime temperatures do rise and peaks tend to decline in time), which may be a consequence of natural variability, of an inadvertent but compensating increase in sulfate aerosol loadup, or of other factors, as well as possible problems with the models.

Deriving a linear temperature trend[3] from the available record is also difficult because it depends strongly on the period over which the trend is calculated. If the period is too short, interannual and other nongreenhouse variations in the temperature can unduly bias the estimate; if it is too long, the records are more subject to problems due to variations in spatial coverage, changes in instrument protocols, etc. Figure 3a shows estimates prepared by T. Karl (MacCracken et al., 1990) of the linear trend starting in years from 1880 to 1939 and ending in 1987. (If he had chosen earlier starting years, the trend would have decreased, and if he had chosen later starting years, it would have again increased.) He also prepared estimates of the trend when starting in 1880 and ending in years from 1930 to 1987 (Figure 3b). The trend is clearly very dependent on the starting and ending dates and does not seem to show an acceleration of the warming with the accelerating increase in greenhouse gas forcing.

If we, with some hesitation, accept that there has been a warming of about 0.5°C over the last 100 years due to the increasing concentration of greenhouse gases (and not amplified or diminished by other factors), this compares with an expectation from model simulations of about 0.4 to 1.6°C (as indicated earlier). In that the late 19th and early 20th centuries were probably somewhat cooler than average due to several large volcanic eruptions (and possibly due to persistence of the Little Ice Age), the warming to date is barely consistent with the lower bound of the theoretical estimates of warming (accepting, again with some hesitation, all of the approximations in deriving those estimates and assuming that no new cooling influences are active). Simplified ocean-atmosphere models also suggest that observations are near the lower bound of the model projections (Bretherton et al., 1990).

The temporal patterns of the observed and expected warmings are also not in accord, especially in the Northern Hemisphere. This may be due to problems with the observations (station moves, urbanization, etc.), with the linearity assumption (could the climate be slightly intransitive?), or with the possible counterbalancing effects of other forcing factors (sulfate aerosols, North Atlantic circulation changes). Over the past decade, several investigators have attempted to reconcile the simulated and observed behavior by accounting for solar and/or volcanic effects; each, however, has arrived at the conclusion that CO_2-induced warming is present, but

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[3] The increase in radiative forcing since 1750 has actually been not linear, but gradually increasing. Nonetheless, a linear trend is most often sought in the absence of better estimates from models.

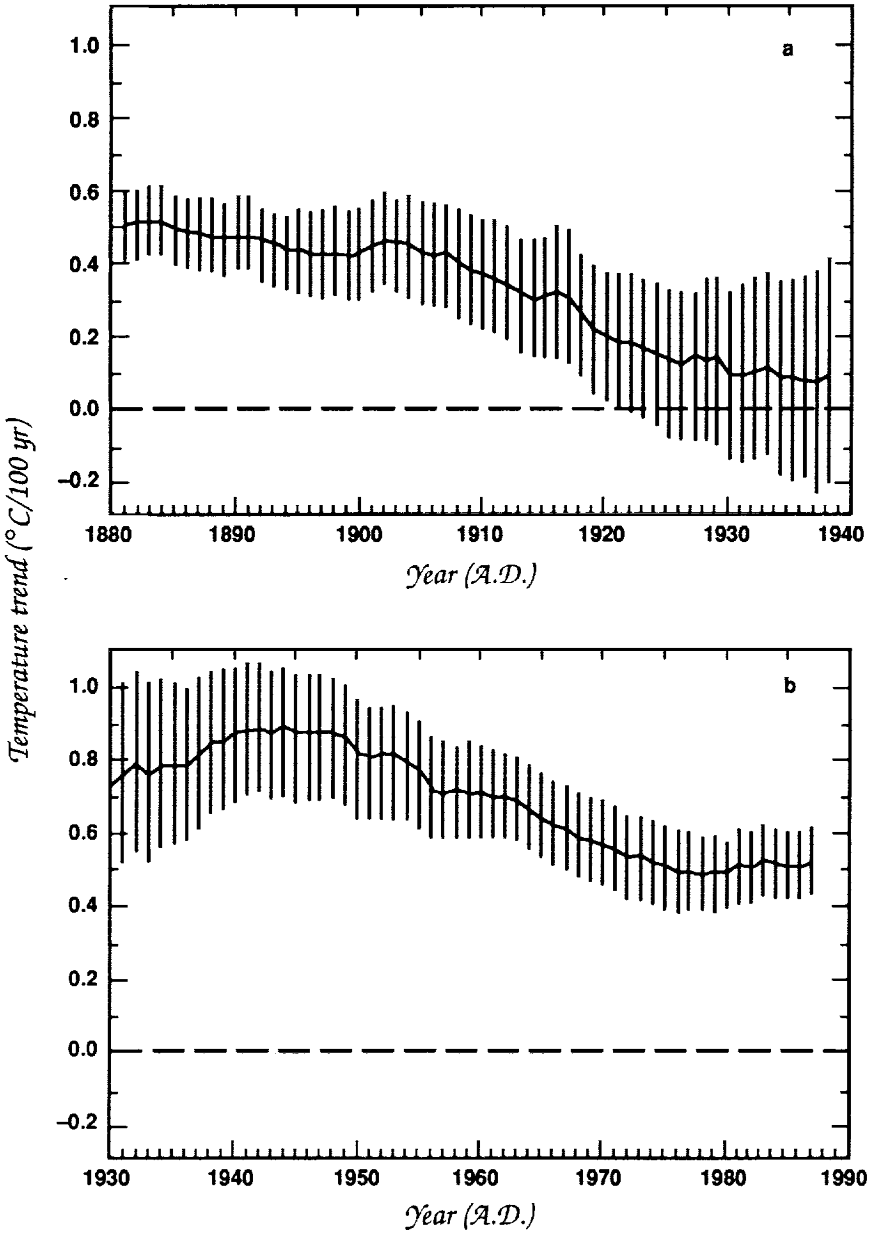

Figure 3. Linear trends of global average land temperatures based on data of Jones (1988) and their associated 95% confidence intervals expressed as rates of change over 100 years: (a) ending year for all trends is 1987, and the beginning year is given on the x axis; and (b) ending year for all trends is given along the x axis, and the beginning year is 1881. Trends reflect changes due to changes in both atmospheric composition and to other natural and human-induced factors (prepared by T. Karl for MacCracken et al., 1990; used with permission).

through inconsistent, and often conflicting, analyses (MacCracken, 1983). Natural variability may also be confounding the analysis. A 1 × CO_2 control simulation by Hansen et al. (1988), for example, shows that the climate may have an inherent natural variability that could be hiding the greenhouse signal (or, conversely, creating much of the recent warming). Without a convincing explanation, the association of the warming with the increases in greenhouse gas concentrations remains captive to uncertainties in our calculations and about the role of natural variability and the influence of other anthropogenic factors.

In addition, the observed and predicted (interpolated) latitudinal patterns of the warming are not in agreement with interpolations from equilibrium calculations (and perhaps should not be expected to be in agreement). Much of the recent warming has been in middle and even low latitudes rather than in high latitudes, as suggested in equilibrium perturbation simulations. However, recent simulations with coupled ocean-atmosphere models suggest that the high-latitude warming may be delayed for very long periods due to the deeper mixing of heat in polar regions. Thus, the importance of this inconsistency may be fading as more realistic calculations become available. Overall, about all that can be said is that warming has occurred over the last century and that some fraction of it (the fraction may range from small to larger than unity) must be due to the increased concentrations of greenhouse gases.

Equally difficult problems arise when considering changes in stratospheric temperature and sea ice extent (for both of which the record is much less complete) and for sea level (for which the prediction and record are both of limited certainty), as explained in the next section. None of the analyses of individual records provides the unequivocal association that is being sought.

The Multivariate Approach

The shortcomings of the individual records suggest that it might prove useful to search for a combination of changes that could be uniquely associated with changes in the concentrations of greenhouse gases (as opposed to volcanic, solar, or other natural influences). Such a *signature* or *fingerprint* approach has great appeal, but has proven quite difficult in practice, because it requires accurate records of multiple variables over comparable periods (the records of the array of variables may not be as long, however, negating some of the benefit of a larger set of variables) and accurate model projections for multiple variables and for all important internal and external changes that may be influencing the climate. As a

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balance to these difficulties, however, the approach enriches consideration of the set of variables by allowing consideration of relative magnitudes and signs of the changes, spatial and seasonal patterns and gradients, correlations, and other aspects.

Elements of a possible signature for the greenhouse gases are shown in Table 2. These indicators have, of necessity, been drawn from equilibrium rather than from transient model simulations. As a result, more comprehensive model simulations may change the fingerprint (and not all characteristics listed have yet been confirmed even in all equilibrium simulations). Three important additional problems exist. First, the records for many of these variables are quite limited; second, it remains difficult to provide quantitative theoretical estimates of these changes; and third, it is not clear that these elements create a sufficiently unique fingerprint for greenhouse gas-induced changes to allow at least some fraction of past changes to be distinguished from changes due to natural variability and to other factors.

Table 2: Possible components of a greenhouse gas-induced climate signal

- *Increasing surface temperature*
  - Strong latitudinal gradient over land
  - Larger changes over land than over the ocean
  - Larger changes during the winter in high latitudes than during the summer
  - Reduced diurnal temperature range
- *Warmer troposphere*
  - Weaker latitudinal gradient
- *Cooling middle and upper stratosphere*
- *Increasing atmospheric water vapor concentrations*
- *Increasing global precipitation*
  - Largest relative change in high latitudes
- *Retreating sea ice cover*
- *Retreating snow cover and mountain glaciers*
- *Rising sea level*

Despite these difficulties, there are preliminary indications that at least some of these changes are occurring; at least, none of the elements are changing strongly in an unexpected direction. The sea level record, for example, appears to be showing a relatively rapid increase (Figure 4).

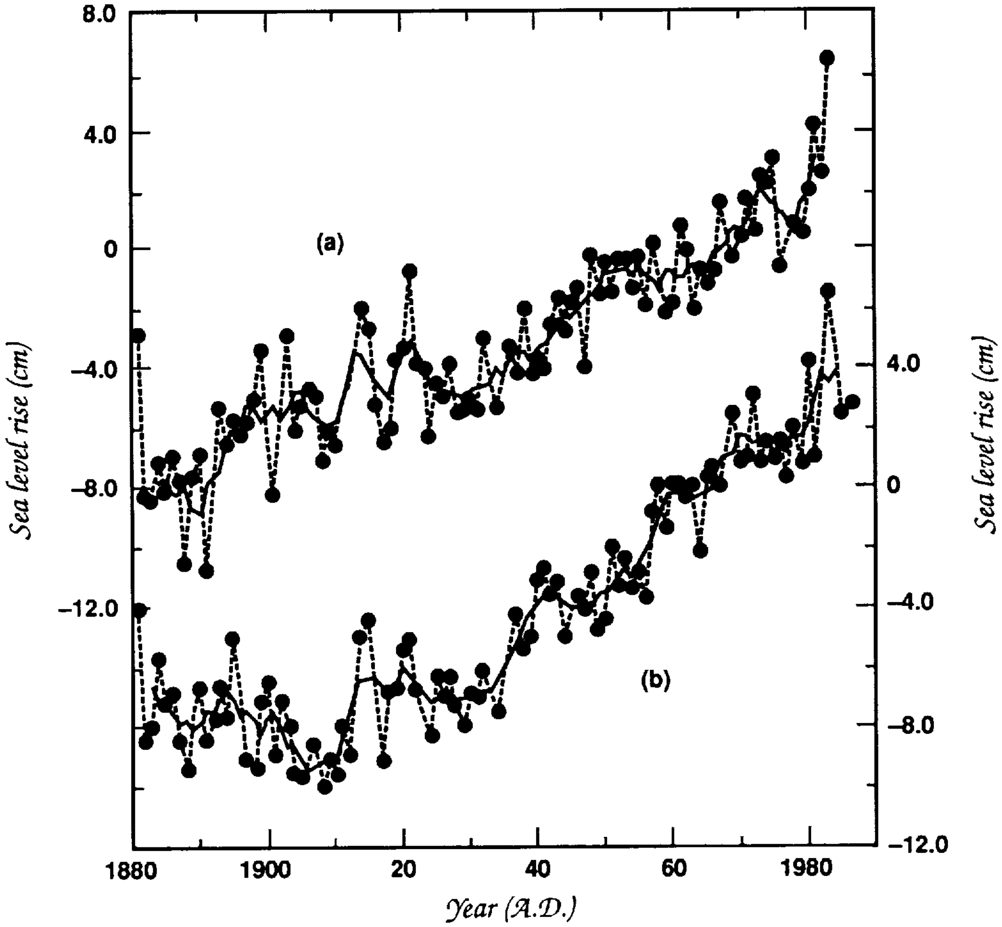

Figure 4. Estimates of global mean sea level rise over the last century. The baseline is arbitrarily selected as the average for the period of 1951 to 1970. The dashed lines connect the annual mean changes (dots); the solid line represents five-year running mean. Data are from (a) Gornitz and Lebedeff, 1987, and (b) Barnett, 1988 (from MacCracken et al., 1990; used with permission).

Again, however, there is not yet quantitative and unequivocal association of the changes with the changes in atmospheric composition.

Conclusions

Observations clearly indicate that the climate has warmed since the mid-19th century—but then, it has warmed before, and the warming since 1850 has not been spatially consistent and temporally monotonic. Clearly, changes due to other factors are also occurring, and we have not been able to quantitatively and uniquely associate the temperature or other climatic changes with the increasing concentrations of greenhouse gases. The collective set of changes that are occurring, however, is certainly suggestive that the enhanced greenhouse effect is starting to have an effect, even though we cannot yet use this determination to narrow our estimates of future change. The situation suggests that we are, in qualitative terms, closer to a civil conviction of the greenhouse gases (i.e., a preponderance of evidence) than to a criminal conviction (i.e., beyond a reasonable doubt) and that, in quantitative terms, there is still homework to do and observations to be gathered before we can substantially strengthen the case.

Acknowledgments

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