Detecting Climatic Change Signals: Are There Any "Fingerprints"?

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Projected changes in the Earth's climate can be driven from a combined set of forcing factors consisting of regionally heterogeneous anthropogenic and natural aerosols and land use changes, as well as global-scale influences from solar variability and transient increases in human-produced greenhouse gases. Thus, validation of climate model projections that are driven only by increases in greenhouse gases can be inconsistent when one attempts the validation by looking for a regional or time-evolving "fingerprint" of such projected changes in real climatic data. Until climate models are driven by time-evolving, combined, multiple, and heterogeneous forcing factors, the best global climatic change "fingerprint" will probably remain a many-decades average of hemispheric- to global-scale trends in surface air temperatures. Century-long global warming (or cooling) trends of 0.5°C appear to have occurred infrequently over the past several thousand years—perhaps only once or twice a millennium, as proxy records suggest. This implies an 80 to 90 percent heuristic likelihood that the 20th-century 0.5 ± 0.2°C warming trend is not a wholly natural climatic fluctuation.

Natural climatic changes are long known (*1*) to have occurred over a spectrum of time and space scales that are the result of a variety of external forcing factors (such as volcanic emissions) or internal processes (such as air-sea interactions). In addition to these natural causes of climatic variation, many potential anthropogenic causes of "global change" have been considered, such as industrial or agricultural emissions of greenhouse gases or sulfur oxides (*2*). It has long been debated whether global warming signals from an anthropogenically enhanced "greenhouse effect" on the one hand or SO_2 emissions and consequent sulfate atmospheric aerosol cooling signals on the other hand can be detected against the background of a highly fluctuating observational temperature record since the 1800s (*3–5*). Univariate measures have been used to determine whether significant anthropogenic climatic change has been detected (*6–8*), but a number of researchers have suggested that such measures, especially globally averaged surface air temperature (9), should be replaced with multivariate methods, which they call fingerprints (*10–12*). These researchers have argued that general circulation models (GCMs) produce regionally heterogeneous maps (for example, some regions get drier while others get wetter and these patterns vary with season) of projected climate change given some scenario of increases in CO_2. Thus, they reason that a much more reliable measure than global temperature of detection of a climate signal would be to compare such seasonally and regionally heterogeneous model forecasts with seasonally and regionally heterogeneous observations of recent climatic trends. This approach would add many additional data points as compared to a single time series of globally averaged surface air temperature and should, they reason (*10–12*), make signal detection occur sooner (*13*).

However, such fingerprints have little practical utility currently and can neither validate nor invalidate most model projections because the model experiment typically performed is an equilibrium CO_2-doubled GCM. Such a model does not match the global change "experiment" (*14*) that the Earth is currently undergoing, in which greenhouse gases and other anthropogenic forcings have been changing over time in a nonuniform way. Indeed, this leads to another aspect of the signal detection problem that needs to be mentioned—namely, the implication of regionally heterogeneous oceanic heat capacity (or thermal inertia) that can delay and distort the appearance of equilibrium climate signals (*15*).

Schneider and Thompson (*16*) have argued that the critical concern for signal detection of regional climate changes is not simply the delay in the rise of the global average surface temperature, attributable to the average thermal lag of the oceans (*17*): It is critical to also consider that regional heterogeneity of heat capacity on Earth could cause a time-evolving signal of climate change that might be of very different character than that predicted by the equilibrium model. That is, an anthropogenic greenhouse radiative forcing of a few watts per square meter globally could lead to much more rapid temperature increases over land than those caused by the same few watts per square meter in the center of tropical oceans with shallow mixed layers. Temperature increases over such oceans in turn would change at a faster rate than surface temperature increases over deeply mixed high-latitude oceans.

Taken together, these spatially differential delay times could cause time-evolving equator-to-pole and land-to-sea temperature gradients during the transient phase that even could be of opposite sign to that in equilibrium (*18*). Indeed, the early generation of coupled atmosphere-ocean GCM results (*19, 20*) suggests that for both dynamic and thermodynamic reasons the transient regional signals can be substantially different than the equilibrium signals in some regions—especially in high-latitude oceanic sectors (*21*).

In a discussion of the detection of forced climate change even in the univariate sense of globally averaged surface temperature, Hasselmann (*22*) noted that internal climate system dynamics could well lead to unpredictable, stochastic "noise" that would mask for decades deterministic forced global signals. Lorenz (*23*) has long argued that there could be chaotic, long-term internal variations in global temperature histories that would add further difficulty in finding forced, deterministic signals. Some simple model calculations (*24*) have lent further credence to the possibility that recent anthropogenic warming has been masked considerably by long-term internal dynamics in the oceans. In any case, it appears that until univariate climatic signals become quite large (for example, many decades with >0.5°C warming on a hemispheric scale or >1°C warming on a continental scale), even globally averaged signals will be lost in oceanic delays and other potential causes, internal and external, of natural variability. This is not to mention also the few tenths of a degree Celsius uncertainty implicit in translating thermometer records of the past century into a global trend of surface air temperature (*25*).

One more aspect of global average temperature trends needs mention. Satellite meteorologists (*26, 27*) have argued that globally comprehensive data sets provided by passive microwave observations from space should be used to give estimates of

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global average temperature. But these estimates suffer because they are not direct in situ temperature measurements, but rather are remotely sensed radiances whose inversion to atmospheric (as opposed to surface) temperatures must account for interfering optical phenomena such as water vapor and clouds as well as problems of calibration due to instrumental drifts over time. In effect, such microwave observations sample the entire troposphere and even a bit of the lower stratosphere (*26, 27*). Moreover, the length of the satellite records is only a decade or so. Thus, although satellite techniques are valuable new tools, the best century-long temperature trend record still remains the corrected and adjusted surface thermometer or low-altitude airborne balloon networks, even if they still carry uncertainty that is equal to approximately half the 20th-century trend (*9*).

The Sun and Aerosols Return as Possible Forcings

For more than 20 years, the sun (*28, 29*), atmospheric aerosols (*4, 30*), or both (*2, 5*) have been postulated as plausible external anthropogenic forcing factors (in addition to greenhouse gases) influencing long-term temperature trends. Recent work has reintroduced the role of the sun in climate forcing. One study (*31*) suggests that rather than looking at the annual sunspot number as the prime correlate with temperature anomalies over the last few centuries (*32*), one should look instead at the time difference between the peaks of the solar cycles. Of course, no one has demonstrated convincingly by measurement or theory that changes observed on the solar disk (such as sunspots or solar diameter) could lead to changes in energy output of the sun that would be nearly sufficient to be responsible for the century-long 0.5°C global warming that has been observed. It has also not been explained why the climate system would respond to a few watts per square meter radiative forcing from the sun but would not respond comparably to a similar radiative forcing from greenhouse gases. In addition, space-borne instruments have not detected solar irradiance changes >0.2% over a solar cycle. Nevertheless, the solar-climate debate of 20 years ago has been rekindled, although most recent studies suggest that there is no more than a modest potential solar influence (*33*).

Atmospheric aerosol impacts from human activities represent another resurfacing of a 20-year-old debate (*2, 3, 30, 34*). Coakley *et al.* (*35*) noted streaks in near-infrared (IR) wavelengths in stratus clouds over the eastern Pacific and determined that these were traces of ship tracks visible in the clouds. This thus lends support to Twomey's (*36*) 25-year-old suggestion for an aerosol–climate change mechanism: Clouds that exist in relatively unpolluted air with a relatively low concentration of cloud condensation nuclei (CCN) can have their albedos increased by the injection of aerosols that act as CCN. Recently, Charlson, Lovelock, Andreae, and Warren (*37*) noted that certain phytoplankton produce a waste product that ultimately leads to dimethyl sulfide injection into the ocean, which diffuses into the atmosphere where it is photochemically converted to sulfate aerosols and eventually into effective CCN. They suggested there might be a biological feedback process influencing climate through sulfate aerosols increasing the cloud albedo by the Twomey mechanism. However, the principal emission of sulfur into the atmosphere is now from anthropogenic sources (*38*). Because human use of energy since the end of World War II has increased severalfold and the principal source of that energy has been fossil fuels that can contain sulfur, such as coal and oil, a dramatic increase in SO_2 could very well have increased sulfate aerosols, and in turn cloud albedo, since 1950.

With regard to aerosols, Kellogg (*39*) plotted what he then called a GNP ("Gross National Pollution") map, which showed a highly regionally heterogeneous pattern of aerosols primarily existing over the northeastern half of the United States and extending hundreds of kilometers downwind over the Atlantic, Europe, Eurasia, and China, and extending downwind into the Pacific. This heuristically determined, regionally heterogeneous pattern (*40*) would probably not offset on a global basis the combined warming effect of anthropogenic greenhouse gases, which Kellogg and most subsequent researchers have assumed to have a relatively homogeneous geographic distribution of global surface layer heating. In the 1970s, this controversy could not yet be resolved. On the other hand, in agricultural regions or industrial zones where SO_2 emissions are high, natural and anthropogenic CCN are likely to be abundant and soot can also be a component of anthropogenic aerosols. Soot particles incorporated into cloud droplets (*41*) could lead to a decrease in cloud albedo.

Given all of the uncertainty about potential aerosol-cloud-albedo processes, Charlson *et al.* (*42*) returned to the potential direct, clear-sky effects of tropospheric sulfate aerosols. These researchers coupled simple radiative, chemical, and transport models and calculated distributions of sulfate aerosols and their potential for reflection of sunlight to space over the globe. They concluded that about one-third of the Northern Hemisphere was covered with anthropogenic sulfate aerosols sufficient to counteract perhaps 50% of the anthropogenic greenhouse heating of the Northern Hemisphere during the past several decades. Aerosol cooling is highly regionally heterogeneous, with strong concentrations over the northeastern United States and immediately downwind over the Atlantic Ocean, Europe, Eurasia, and China (a close replica of those regions in the intuited Kellogg map).

At the same time, Karl *et al.* (*25*) noted that most of the surface warming of the past three decades over the United States, the former Soviet Union, and China took place at night—precisely in those places where sulfur emissions were the highest (*43*); of course, anthropogenic greenhouse heating would take place day and night, but direct aerosol-induced radiative cooling would happen primarily when the sun shone. Is this nighttime warming observational "proof" of a partial sulfate offset to an otherwise anticipated 1°C global-warming signal predicted by GCMs or yet another coincidence? Appropriately, that question is still debated (*44*), because no one should consider a few decade, <1°C temperature trend record over 30% of one hemisphere as conclusive proof of the magnitude of global climate sensitivity to radiative heating or cooling forcings. Nonetheless, it is intriguing and appears consistent with heterogeneous anthropogenic forcings.

A few years earlier, Wigley (*45*) anticipated the reemergence of aerosols in the debate about the detection of anthropogenic climate signals, noting that the Northern Hemisphere had not warmed up more than the Southern Hemisphere in the past century, although the Southern Hemisphere has more oceanic surface and thus a higher heat capacity. Models have long suggested (*16*) that the Southern Hemisphere should thus have warmed up more slowly than the northern zones. Wigley suggested that perhaps this not having happened is at least circumstantial evidence of an anthropogenic SO_2-induced retardation of the anticipated warming signal in the Northern Hemisphere, which helps to explain why the Northern Hemisphere warmed up only 0.5°C, whereas most models with sensitivity in the "canonical" 3° ± 1.5°C warming range for 2× CO_2 (CO_2 doubling) suggest that the Earth should have warmed up 1° ± 0.5°C (*46*). In essence, we need to get the net solar-IR radiative forcing to an accuracy of at least 0.5 W m^{-2} at a global scale (*47*).

Regional Teleconnections from Heterogeneous Forcing

Regional anomalies in sea-surface temperatures (SSTs) have coincided with unusual weather patterns both within the region of the SST anomaly and potentially far downstream (48). Moreover, Dickinson (49) calculated theoretically that regionally heterogeneous atmospheric forcing could lead to regionally heterogeneous atmospheric responses, similar to the teleconnections that Bjerknes or Namias had long postulated to exist on the basis of semiempirical studies (48). Early GCM calculations by Chervin, Washington, and Schneider (50) suggested that far downstream teleconnections from mid-latitude ocean temperature anomalies would be hard to detect above the noise of natural atmospheric variations, but other early studies (51) suggested that tropical SST anomalies (for example, El Niño events) had much more statistically significant atmospheric signals—not only in the region of the anomalies, but, as recent observational studies show, through teleconnections as well (52).

Thus, if aerosols add a major measure of regional heterogeneity to anthropogenic radiative forcing, the climatic response to be detected would be a complicated function of (i) globally averaged net radiative forcing and regional dynamical responses ("teleconnections") from regionally heterogeneous forcing and (ii) complications arising from transient response factors associated with inhomogeneous oceanic mixing processes and the heat capacity of the Earth's surface. Perhaps tropical aerosols from biomass burning (53) could have a significant regional teleconnections signal if the earlier studies of the sensitivity of the atmosphere to tropical SST anomalies extrapolate to tropical aerosol–induced regional forcing anomalies.

Heterogeneous Net Anthropogenic Radiative Forcing

Kiehl and Briegleb (54) have pointed out a new complexity: regionally heterogeneous greenhouse radiative forcing that had been assumed by most analysts to be quite homogeneous relative to aerosol forcing. Kiehl and Briegleb calculated a spatial difference of almost a factor of 5 in anthropogenic IR radiative heating ("greenhouse gas forcing") of the surface troposphere system. Their calculation of this range is a result of the presence of other constituents that are radiatively active in the IR—in particular, the assumed cloud cover distribution they used. This critical latter factor is partly a result of limited observations—it mixes observations with cloudiness maps produced from the control run of the most recent version of the National Center for Atmospheric Research (NCAR) community climate model series, CCM2 (55). The IR heat-trapping capacity of cirrus clouds or high-altitude thick clouds has long been known (56, 57) to lead to a substantial greenhouse effect. Therefore, the solar reflection and heat-trapping capabilities of such high-altitude cloud-top regions therefore reduces the relative importance of any additional IR opacity introduced by the addition of anthropogenic greenhouse gases (58). High-altitude clouds also override the bulk of the radiative effects of underlying aerosols.

Given the highly spatially heterogeneous nature of the combined anthropogenic aerosol and greenhouse gas radiative forcing (Fig. 1), regionally heterogeneous forcing of any kind could be responsible for significant regional climatic anomalies (as discussed earlier in the context of observational and modeling studies of atmospheric "teleconnections"). Because of this, it is of importance to multivariate signal detection studies that credible regional radiative forcing be used for models whose signals will be checked against observations to see if the fingerprints match. Moreover, because the three-dimensional (3D) distribution of clouds used by Kiehl and Briegleb is partly model generated and because model-generated cloudiness is not yet a well-validated variable, many sensitivity studies with alternative cloudiness formulations need to be used to calculate the regional heating or cooling associated with greenhouse gas or SO_2 emissions. As for the aerosol forcing, nobody has tried to produce a regional map of CCN-induced (or soot-induced) cloud albedo changes, although net global effects have been estimated (59). Thus, this additional 20-year-old potential contribution to the heterogeneous nature of the radiative forcing is yet to be part of the already quite dramatic asymmetric radiative forcing that Fig. 1 demonstrates.

Anthropogenic Preindustrial Forcing May Be Overestimated

I will now argue that the method used by Kiehl and Briegleb (and many others, as well) to calculate long-term radiative forcing probably leads to underestimates of the climatic sensitivity that might be inferred from Fig. 1 because this figure probably overestimates radiative forcing from the preindustrial (PI) period to the present. To produce Fig. 1, these authors combined the increase in greenhouse gases from PI concentrations calculated by the Intergovernmental Panel on Climate Change (IPCC) (11), along with the anthropogenic sulfate distributions from the calculations of Langner and Rodhe (60), and added improved radiative transfer calculations. The latter appear more physically comprehensive than those of Charlson *et al.* (42) and in fact produce only half of the radiative offset effects of aerosols in comparison to those of Charlson *et al.* (42). Nevertheless, the combined maps of greenhouse and sulfate forcing (Fig. 1) show dramatic spatial differences, with regions (half a continent in size) of net radiative cooling in highly SO_2-polluted areas mixed with smoother, but still globally inhomogeneous radiative heating attributable to anthropogenic greenhouse gases.

However, there may be potentially important inconsistencies between the calculations of Kiehl and Briegleb and the total anthropogenic forcing that has actually occurred during the past 100 to 200 years. The primary reason is that their calculations use anthropogenic forcing data from IPCC, which show an increase over the last two centuries, but present-day 3D distributions from observations, models, or both of temperature and optically active atmospheric constituents. That is, Kiehl and Briegleb's calculations neglect the actual temperature or related compositional changes (such as water vapor concentration) that have taken place in the last two centuries—a time in which temperature increases of 0.5° to 1.0°C globally are documented (11). Moreover, Manabe and Wetherald (56) pointed out nearly 30 years ago that surface temperature change and water vapor concentrations are tightly connected. Thus, possible climatic changes over the past two centuries could have combined with increasing anthropogenic forcing to make the spatially heterogeneous pattern of net radiative forcing calculated by Kiehl and Briegleb a possible overestimate of both cooling in high-sulfate concentration zones and warming in the rest of the world.

The heating or cooling perturbations from some radiative forcing can be decomposed into several factors. First is the direct effect of a change in radiatively active constituents (such as CO_2 or H_2SO_4) on heating rates with all other factors being constant (that is, no temperature, water vapor, ice, or cloud feedback effects). This is what is assumed to compute the net radiative forcing map (Fig. 1). Second is simply the effect of greenhouse forcing on atmospheric temperature changes and therefore a subsequent increase of downward IR radiative flux. Third is the effect of warming on evapotranspiration and the well-established water vapor–temperature–greenhouse feedback. The latter two processes are generally thought to be strong positive feedbacks (61, 62). Therefore, the implicit inclusion of the latter two feedback processes during the probable 0.5° to 1.0°C global warming since the PI era could render the Kiehl and Briegleb map an overestimate of the actual strength and heterogeneity of anthropogenic radiative forcing circa 1800.

Kiehl and Briegleb also neglect cloud

albedo effects from aerosols and land surface changes. They also use climate-model output variables to help compute their present-day heating perturbations, whereas in reality some of these variables probably changed over time. Without actually specifying the heterogeneous, 3D, long-term changes in the time history of atmospheric temperature and optically relevant composition, it is impossible to make a quantitative correction to the Kiehl and Briegleb maps. Reducing uncertainties in a two-century record of climatic changes is a formidable problem, and indeed I do not fault these authors for its neglect at this stage.

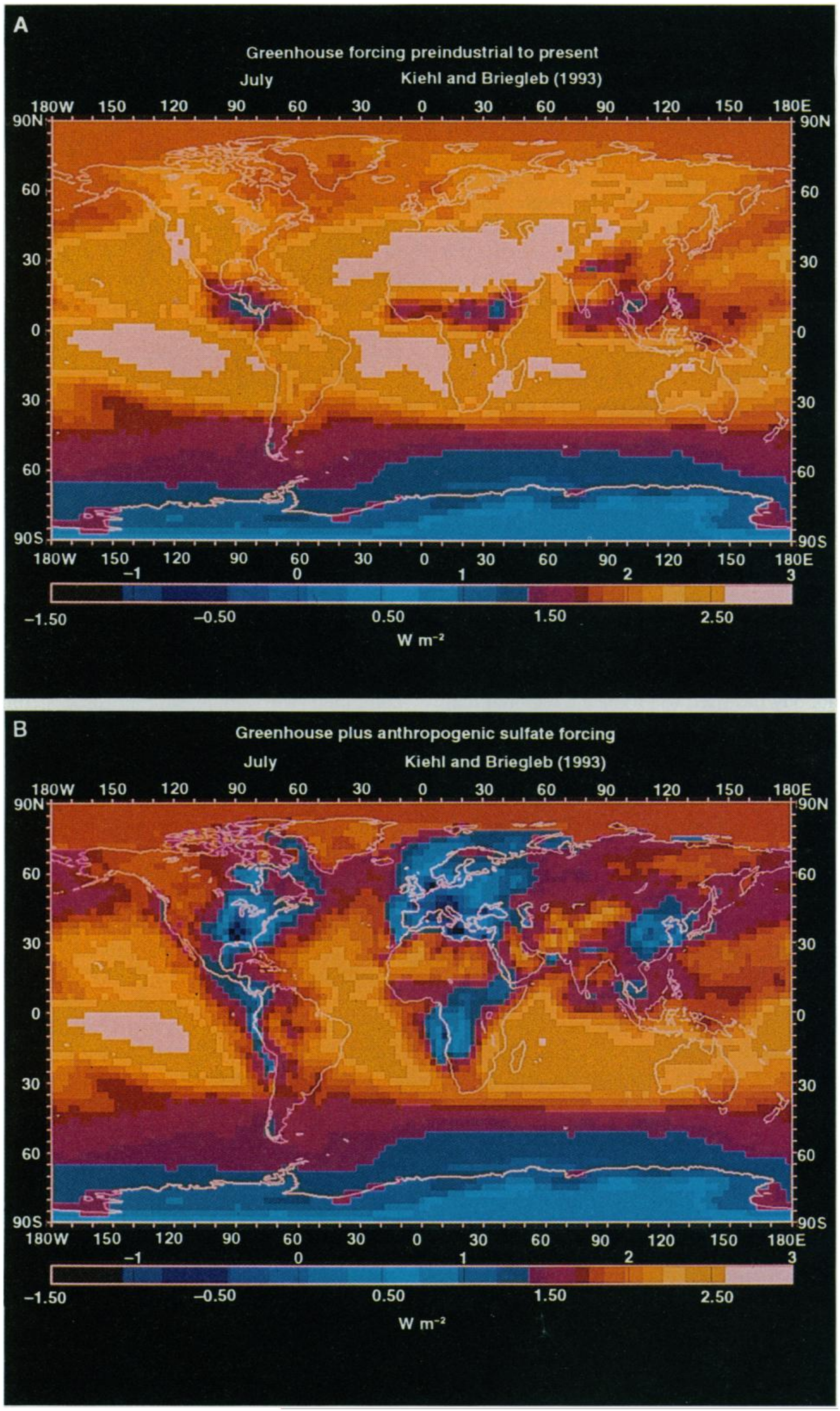

Fig. 1. (**A**) July averaged greenhouse forcing (in watts per square meter) from increases in CO_2, CH_4, chlorofluorocarbon-11 (CFC-11), and CFC-12 from preindustrial time to the present (annual global average = 2.1 W m^{-2}). (**B**) July averaged greenhouse forcing plus anthropogenic sulfate aerosol forcing (in watts per square meter) (annual global average = 1.8 W m^{-2}), as calculated by Kiehl and Briegleb (*54*). [This figure is modified after Kiehl and Briegleb (*54*), copyright 1993 by AAAS.]

In view of the 20-year-old controversy (*63*) over the effect of various climatic feedback processes on climate sensitivity, it is important to calculate the net radiative forcing since the PI era as accurately as possible. This term is needed to estimate empirically the climate sensitivity parameter

$$\lambda_{PI} = \Delta T/\Delta F_{PI} \qquad (1)$$

where ΔF_{PI} is PI to present-day radiative forcing in watts per square meter and ΔT is the anticipated equilibrium global temperature response (the "climate signal") in degrees Celsius.

However, I believe we can draw some quantitative estimates from Ramanathan's analysis (*61*) as to the magnitude of possible feedback mechanisms that may have been lumped into the calculations for Fig. 1. Table 1, from Ramanathan (*61*), shows results for a CO_2-doubling calculation in a one-dimensional radiative-convective model in which three basic processes are shown. Process 1 is direct surface heating by CO_2, which with the doubling of CO_2 causes an increment of net surface radiation, ΔR, of ~1.2 W m^{-2} (*64*).

Process 2 in Ramanathan's table is the direct warming of the surface-troposphere system, which makes lower atmospheric temperatures warmer. This, in turn, enhances the upward and downward IR emission by (fixed concentrations of) radiatively active constituents in the troposphere such as clouds, H_2O, CO_2, and methane. Then, the downward component of this enhanced IR radiation is added to the surface warming calculated by process 1 alone. Both of these processes together lead to an increased surface layer temperature, ΔT.

Table 1. Radiative forcing from CO_2 doubling calculations of Ramanathan (*61*). Process 1, direct surface heating; process 2, direct tropospheric heating; process 3, indirect surface temperature–water vapor–greenhouse heating. ΔT is model-dependent.

Radiative forcing effects	Flux (W m^{-2})	Percent of total flux	ΔT
Process 1	1.2	8.0	0.17
Process 2	2.3	15.0	0.33
Process 3	12.0	77.0	1.7
Total surface-tropospheric heating from 2× CO_2	15.5	100.00	2.2

Process 3 is the classical "water vapor–temperature–greenhouse feedback" that is parameterized in energy-balance climate models by fixing relative rather than absolute humidity, as first noted by Manabe and Wetherald (*56*) and later empirically incorporated into the IR radiative transfer parameterizations (*65*). Water vapor–temperature feedback is internally generated by all modern GCMs (*66*). Raval and Ramanathan (*62*) demonstrated that this very strong, positive feedback seems to be well modeled at a large scale in GCMs, as based on intercomparisons between GCM results and IR radiative fluxes leaving the Earth's atmosphere as measured by satellites (*67*).

There are two aspects of this process that need expansion. First is Ramanathan's assumption (*67*) that the water vapor–greenhouse effect feedback occurs primarily over oceans. This assumption was based on a then-prevailing view that assumed land surface evapotranspiration processes to be vastly subordinate to evaporation over the oceans. However, hydrologic studies from observations over the Amazon (*68*) or modeling studies show that land surface evapotranspiration can account for a substantial fraction of atmospheric moisture content, if not the vast majority of water vapor that fuels summertime deep convective activity over land. Indeed, modern biophysical, land surface parameterizations such as the Biosphere-Atmosphere Transfer Scheme (*69*) show a very strong link between surface temperature, net surface radiation, and the evapotranspiration of moisture through vegetation, which then becomes available for water vapor–temperature feedback or convective activity over land (*70*).

Kiehl and Briegleb used a current 3D distribution of temperature, cloudiness, and water vapor in the atmosphere along with two centuries' worth of data on anthropogenic emissions to calculate anthropogenic radiative forcing. Because of this, in the Kiehl-Briegleb calculation any enhanced heating or cooling feedback processes associated with Ramanathan's processes 2 and 3 (Table 1) based on whatever long-term trends since PI times in temperature, moisture, or any other optically important factors that actually occurred would be lumped into ΔF_{PI}. The warming of the surface or of the atmosphere has not been homogeneous, and there are regions of cooling and seasonal and diurnal deviations from global trends (*25, 71*). Thus, the actual forcing map that would be needed for a calculation to be used in any climatic change signal detection study could be less accentuated than that of Kiehl and Briegleb.

Of course, without 3D observations of the actual 19th- and 20th-century trends in temperature and optically active constituents in the atmosphere, we can only guess at how Kiehl and Briegleb's map should be quantitatively redrawn. It could be argued by analogy from Ramanathan's results for CO_2 doubling that feedback processes such as 2 and 3 in Table 1 might have enhanced the depth of the cooling rate or the highs of the heating rate on the Kiehl-Briegleb map by some 25 to 50% in regions of maximum or minimum forcing. This magnitude of change would represent a nontrivial addition to the potential semiempirical calculation of climate sensitivity parameter, λ_{PI}, from Eq. 1. That is (using round numbers), if ΔT from 1800 to the present is assumed to be 1°C and $\Delta F_{PI} = 2$ W m^{-2} (*54*), then

$$\lambda_{PI} = 1 \div 2 = 0.50°C/W\ m^{-2} \quad (2)$$

This implies warming for CO_2 doubling

$$\Delta T_{2\times} = 0.50 \times \Delta F_{2\times} \quad (3)$$

where $\Delta F_{2\times} \approx 3.0$ W m^{-2} (*61*). This in turn implies

$$\Delta T_{2\times} = 0.50 \times 3.0 = 1.5°C \quad (4)$$

which is typical of that estimated semiempirically from greenhouse gas forcing alone (*33, 46*). However, if ΔF_{PI} were overestimated by 50%, for example, from lumping feedback processes 2 and 3 into the forcing calculation, then from Eq. 1 the semiempirically determined value for λ_{PI} would be doubled, as would the CO_2-doubling climate sensitivity $\Delta T_{2\times}$ (3°C in these round numbers).

There is a second issue surrounding feedback process 3 (*67*): There is disagreement, occasionally heated, about whether cumulus activity will serve as a strong negative feedback on radiation forcing or if water vapor–greenhouse feedback is dominant and more likely to be strong and positive. Ellsaesser (*72*) first suggested one possible convective cloud negative feedback mechanism involving drying of the upper troposphere. His idea was forcefully elaborated on by Lindzen (*73*), although their confidence in such a strong negative feedback on a global scale has been disputed (*27, 74*) and has even led to debates in front of the U.S. Senate (*75*). Recently, Sun and Lindzen (*76*), following up on a suggestion by Betts (*77*), now argue that the neglect of evaporation of falling high-altitude ice or water particles may reconcile the dispute and explain why observations were not consistent with Lindzen's original (*73*) arguments for upper troposphere drying.

Do Fingerprints Exist?

The combination of regionally heterogeneous anthropogenic aerosol forcing and greenhouse gas net radiative forcing onto one map is an important insight of Kiehl and Briegleb. I suspect that the Kiehl and Briegleb map of net anthropogenic radiative forcing (Fig. 1) will remain qualitatively instructive, even if factors such as two-century-long trends in atmospheric temperature, humidity, cloudiness, and other optically active constituents were somehow able to be included. I have suggested that the forcing highs could get 25 to 50% lower, and the lows might get comparably higher. This would lead to a significant increase in the semiempirically determined global-average climate sensitivity to net radiative forcing from the PI period to the present.

What does all this imply for fingerprints and the detection of any anthropogenic climate signal? In order to approach this regional level of detail credibly, we need a transient earth systems model (ESM)—that is, coupled atmosphere-ocean-land surface-biota-ice-chemical models that include adequate resolution of 3D cloudiness distributions, including cloud heights (with cirrus), as Kiehl and Briegleb have wisely reminded us. We will also require models with appropriate surface-process packages to deal with evapotranspiration feedbacks, which could alter the calculation of forcing patterns over land and sea. Moreover, a spatially heterogeneous net radiative forcing will be needed for the calculation of any globally averaged residual effects (*78*) and for credible forecasts of time-evolving, regional climatic response, as suggested a decade ago (*16, 18*).

This does not bode well for the viability of multivariate, regional-scale fingerprint techniques. We need not just a regional scale of model resolution for the calculated climatic response to be comparable to the "experiment" that the climate system is currently undergoing. We must also force our regionally resolved ESMs with a realistic, time-evolving, regionally heterogeneous set of anthropogenic net radiative forcings before those fingerprints would have any meaning for validating any model driven by such forcing maps. One interim strategy might be an "ensemble" (at least a few dozen) of GCM runs, each driven with realistic regional maps of net radiative forcings to generate a set of GCM fingerprint test maps (*79*). Unfortunately, observations of atmospheric, oceanic, biological, subsurface, and chemical variables needed to validate many aspects of such coupled climate systems model runs are also decades away (*11, 80*).

What, then, is the appropriate path for the scientific community to pursue? It seems to me that in principle the answer is actually very straightforward (but not easy in practice): Work across many scales and disciplines to understand physical, chemical, biological, and relevant societal processes, their interactions, the heterogeneity in net radiative forcing they imply, the implications of transient, heterogeneous forcings for the Earth systems response, and the synergisms that will be discovered from coupled Earth systems research (*81*).

For the detection of anthropogenic climatic signals, we must recognize that a goal of 99% statistically significant signal detection over the next decade or two is unrealistic, unless the global net anthropogenic forcing is known to better than 0.5 W m^{-2} and is thus large enough that "noise" from solar, volcanic, and other "minor" natural perturbations can be overcome. We also should temper the expectation (*13*) that fingerprints of regionally heterogeneous, time-evolving signals could either speed up that signal detection process or refute model forecasts; I suspect that accounting for the extra complexity involved in the regionally heterogeneous, but still very uncertain, net anthropogenic radiative forcing may actually delay credible multivariate detection techniques relative to the old, simple univariate methods. With regard to the latter, when sustained century-long temperature change exceeds a degree Celsius on a hemispheric basis or half a degree on a global scale, it is pretty much outside the range of most century-long natural fluctuations experienced in the past several thousand years. The reason is that such trends appear perhaps no more often than once or twice a millennium, as might be inferred by proxy analyses such as tree ring or glacial moraine time series (*82*). However, assigning formal statistical significance levels to anthropogenic signal detection exercises may actually be an intellectually misleading exercise because fundamental uncertainties remain in the assumptions as to (i) what the long-term, low-frequency natural variability of the climate system is and (ii) what the various forcings were that created the suspected climatic "response."

Finally, one must think carefully with regard to the policy debate and the advice to wait until we are 99% statistically confident that signals have been detected before we act to reduce anthropogenic emissions. We must remember that how to act in the face of the whole range of global-change possibilities is a value judgement about risk management (*83*). It is not a question directly answerable with technical analyses, such as the best strategy to improve the credibility of signal-detection estimates.

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13. In (*11*), this opinion was offered: "The fingerprint method, which involves the simultaneous use of more than one time series, is the *only* [emphasis added] way that the [signal] attribution problem is likely to be solved" (p. 252). The appropriateness of the word "only" is questioned later on.
14. R. Revelle and H. E. Suess [*Tellus* **9**, 18 (1957)] first referred to the anthropogenic injection of CO_2 as a great "geophysical experiment."
15. K. Hasselmann [in *Man's Impact on Climate*, W. Bach, J. Pankrath, W. Kellogg, Eds. (Elsevier, New York, 1979), pp. 43–55] noted that the thermal response time of the climate system could not be viewed as a single number (that is, a global average of the atmospheric surface temperature delay time). This is because the atmospheric surface temperature response over land would proceed toward its equilibrium value at one rate, whereas the mixed layer of the oceans would proceed at another rate (perhaps an order of magnitude slower); the deep oceans would proceed at a rate another order of magnitude slower toward its equilibrium response. B. G. Hunt and N. C. Wells [*J. Geophys. Res.* **84**, 787 (1979)] calculated with a simple one-dimensional diffusion ocean model delays of decades or more in the response of the global surface temperature to thermal forcing. S. L. Thompson and S. H. Schneider [*J. Geophys. Res.* **84**, 2401 (1979)] calculated similarly, using a zonally averaged energy balance model, as did M. I. Hoffert, A. J. Callegari, and C. T. Hsieh [*J. Geophys. Res.* **85**, 6667 (1980)], using a slightly more realistic upwelling diffusion ocean model.
16. S. H. Schneider and S. L. Thompson, *J. Geophys. Res.* **86**, 3135 (1981).
17. The thermal lag of the oceans to radiative forcing is itself sensitive to various heterogeneous and nonlinear mixing processes within the oceans; see, for example, L. D. D. Harvey and S. H. Schneider [*J. Geophys. Res.* **90**, 2192 (1985)].
18. Because anomalies in such horizontal surface temperature gradients help to create regional anomalies in climate, Schneider and Thompson (*16*) argued that a time-evolving regional pattern of climate change could be different in the transient run than in equilibrium. K. Bryan, F. G. Komro, S. Manabe, and M. J. Spelman [*Science* **215**, 56 (1982)] showed that that may not be too serious a problem in a model with a zonally homogeneous land-sea fraction. However, S. L. Thompson and S. H. Schneider [*ibid.* **217**, 1031 (1982)] countered that with realistic land-sea distribution (or rapidly increasing forcing over time), one would indeed expect much slower responses in the more oceanic, higher Southern Hemispheric latitudes than elsewhere and that it will take validated, fully coupled 3D atmosphere-ocean models driven by realistic scenarios of time-evolving radiative forcing to produce reliable estimates of time-evolving regional climatic anomalies. This is the level of resolution needed for consistent multivariate fingerprint analyses against observational trend data.
19. W. M. Washington and G. A. Meehl, *Clim. Dynam.* **4**, 1 (1989).
20. R. J. Stouffer, S. Manabe, K. Bryan, *Nature* **342**, 660 (1989).
21. Schneider and Thompson (*16*) used an energy balance model in which only heat capacity varied from latitude to latitude; the coupled air-sea GCMs typically use dynamical oceanic models coupled to 3D dynamical atmospheric models. In one (*20*), for example, their mid-latitude southern oceans exhibited a very slow thermal response to CO_2 increases, and thus little warming signal, in a 100-year transient run at 40° to 60°S. The slow thermal response resulted not only from the high heat capacity of that zone, but also from feedback processes within the oceans in which they simulated enhanced local mixing.
22. K. Hasselmann, *Tellus* **28**, 473 (1976).
23. E. N. Lorenz, *Meteorol. Monogr.* **8** (no. 30), 1 (1968).
24. R. C. Watts and M. C. Morantine, *Clim. Change* **18**, iii (1991).
25. See T. R. Karl *et al.*, *Geophys. Res. Lett.* **18**, 2253 (1992); T. R. Karl, *Res. Explor.* **9**, 234 (1993).
26. R. W. Spencer and J. R. Christy, *Science* **247**, 1558 (1990); IPCC, *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, J. T. Houghton, G. J. Jenkins, J. J. Ephraums, Eds. (Cambridge Univ. Press, Cambridge, 1992).
27. W. W. Kellogg, *Bull. Am. Meteorol. Soc.* **72**, 499 (1991).
28. J. A. Eddy, *Science* **192**, 1189 (1976); K. Ya. Kondratyev and G. A. Nikolski, *Q. J. R. Meteorol. Soc.* **96**, 509 (1970).
29. R. L. Gilliland and S. H. Schneider, *Nature* **310**, 38 (1984).
30. R. A. Bryson, *Weatherwise* **21**, 56 (1968); R. J. Charlson and M. J. Pilat, *J. Appl. Meteorol.* **8**, 1001 (1969); S. I. Rasool and S. H. Schneider, *Science* **173**, 138 (1971).
31. E. Friis-Christensen and K. Lassen, *Science* **254**, 698 (1991).
32. For example, this was done by many (*5, 7, 8, 28, 29*); C. Mass and S. H. Schneider, *J. Atmos. Sci.* **34**, 1995 (1977).
33. Several researchers have recently attempted to obtain a best fit between long-term (univariate) global average temperature and climatic model output arising from various forcing function inputs, such as greenhouse gases, aerosols, or solar irradiance changes with time. Two recent studies agree that solar forcing can help to explain the observed century-long trend in surface air temperature, although the "dominant contribution to the observed temperature changes" since the 19th century is increased greenhouse gases. Two such studies are P. M. Kelly and T. M. L. Wigley, *Nature* **360**, 328 (1992); and M. E. Schlesinger and N. Ramankutty, *ibid.*, p. 330.
34. R. J. Charlson and M. J. Pilat, *J. Appl. Meteorol.* **10**, 841 (1971); S. H. Schneider, *ibid.*, p. 840.
35. J. A. Coakley Jr., R. L. Bernstein, P. A. Durkee, *Science* **237**, 1020 (1987).
36. See figure 8.9, p. 299, in (*2*) for Twomey's suggestion.
37. R. J. Charlson, J. E. Lovelock, M. O. Andreae, S. G. Warren, *Nature* **326**, 655 (1987).
38. See table 1 of S. E. Schwartz, *ibid.* **336**, 441 (1988); J. H. Hahn *et al.*, in *Atmospheric Chemistry*, E. D. Goldberg, Ed. (Springer-Verlag, New York, 1982), pp. 181–198.
39. W. W. Kellogg, *Effect of Human Activities on Global Climate* (World Meteorological Organization, Geneva, 1977).
40. Kellogg constructed it by assuming aerosol injection was proportional to the gross national products of the countries of the region, and by eye he "transported" this gross national product signal downwind to draw his "Gross National Pollution" maps.
41. As noted by G. D. Robinson more than 20 years ago as well; see figure 8.7, p. 218, in (*2*).
42. R. J. Charlson, J. Langner, H. Rodhe, C. B. Leovy, S. G. Warren, *Tellus* **43**, 152 (1991).
43. M. Engardt and H. Rodhe, *Geophys. Res. Lett.* **20**, 117 (1993).
44. R. A. Kerr, *Science* **255**, 682 (1992).
45. T. M. L. Wigley, *Nature* **339**, 365 (1989).
46. See also Hansen *et al.* (*7*) and Gilliland and

Schneider (*29*) for early discussion of this issue; Watts and Morantine (*24*) and W. W. Kellogg [*Clim. Change* **25**, 85 (1993)] have suggested deep oceanic overturning as another possible explanation for this discrepancy between most calculated GCMs and global temperature observations.
47. I select this <0.5 W m^{-2} accuracy because observational and modeling studies [see the appendix of Schneider and Mass (*5*), or chapters 1 and 10 in K. E. Trenberth, Ed., *Climate System Modeling* (Cambridge Univ. Press, London, 1992)] suggest that the equilibrium sensitivity parameter λ ($=\Delta T/\Delta F$) of the global mean surface temperature change ΔT to net radiative forcing ΔF is typically calculated in a range of 0.33 to 1 K W^{-1} m^{-2} of net global radiative forcing. Thus, 0.5 W m^{-2} uncertainty in ΔF would imply uncertainty in ΔT of 0.167 to 0.5 K, the latter already being too high an uncertainty if we are to achieve early detection.
48. J. Bjerknes, *Mon. Weather Rev.* **97**, 163 (1969); J. Namias, *Tellus* **4**, 336 (1972).
49. R. E. Dickinson, *Mon. Weather Rev.* **99**, 501 (1971).
50. R. M. Chervin, W. M. Washington, S. H. Schneider, *J. Atmos. Sci.* **33**, 413 (1976).
51. P. R. Julian and R. M. Chervin, *Mon. Weather Rev.* **106**, 1433 (1978); P. R. Rowntree, *Q. J. R. Meteorol. Soc.* **98**, 290 (1972).
52. K. E. Trenberth, G. W. Branstator, P. A. Arkin, *Science* **242**, 1640 (1988).
53. J. E. Penner, R. E. Dickinson, C. A. O'Neill, *ibid.* **256**, 1432 (1992).
54. J. Kiehl and B. P. Briegleb, *ibid.* **260**, 311 (1993).
55. "Description of the NCAR Community Climate Model (CCM2)," NCAR/TN-382+STR (1993).
56. S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* **24**, 241 (1967).
57. S. H. Schneider, *ibid.* **29**, 1413 (1972).
58. V. Ramanathan and W. Collins [*Nature* **351**, 27 (1991)] found from satellite observations that over very warm waters, shielding by cumulus clouds and associated cirrus clouds could produce a significant negative feedback that would prevent increases in ocean surface temperatures much beyond 300 to 305 K.
59. Y. J. Kaufman, R. S. Fraser, R. L. Mahoney, *J. Clim.* **4**, 578 (1991); Y. J. Kaufman and M. D. Chou, *ibid.* **6**, 1241 (1993). These researchers suggest that aerosol-induced cloud albedo increases could cut anticipated global greenhouse warming by 25% in 2040 A.D.
60. J. Langner and H. Rodhe, *J. Atmos. Chem.* **13**, 225 (1991).
61. As calculated, for example, by V. Ramanathan [*J. Atmos. Sci.* **38**, 918 (1981)].
62. The calculations in (*61*) are supported empirically by A. Raval and V. Ramanathan [*Nature* **342**, 758 (1989)].
63. S. H. Schneider, *J. Atmos. Sci.* **32**, 2060 (1975); (*2*).
64. This change occurs from the assumption of CO_2 doubling and is the same magnitude as ΔF_{PI} calculated by Kiehl and Briegleb (*54*). However, these values should not be directly compared because ΔR is only for the surface, whereas ΔF_{PI} = 2 W m^{-2} from (*54*) is based on their calculation of the forcing of the entire surface-troposphere system. Ramanathan computes this latter forcing from CO_2 doubling to be ~3 to 4 W m^{-2}. The causes of the differences between surface and surface-tropospheric heating are well known and have been used (*61, 63*) to explain the discrepancies between the low sensitivities of surface energy-balance models (*84*) and higher sensitivity earth-atmosphere system model calculations, which more correctly (in one-dimension) account for the relevant energy balance flows in the earth-atmosphere system.
65. M. I. Budyko, *Tellus* **21**, 611 (1969); W. D. Sellers, *J. Appl. Meterol.* **8**, 392 (1969); S. G. Warren and S. H. Schneider, *J. Atmos. Sci.* **36**, 1377 (1979).
66. W. M. Washington and C. L. Parkinson, *An Introduction to Three-Dimensional Climate Modeling* (University Science, Mill Valley, CA, 1986).
67. Ramanathan suggests that "this feedback between temperature, H_2O evaporation, and IR emission is primarily controlled by the ocean-atmosphere interactions since world oceans are the primary source of atmospheric H_2O. The magnitude of the amplification is strongly determined by tropospheric convective adjustment processes and its subsequent effect on tropospheric lapse rates. This dependence arises because the partitioning of the IR emission between upward and downward components is controlled by lapse rate changes" [(*61*), p. 921].
68. E. Salati, A. Dall Ollio, J. Gat, E. Matsui, *Water Resour. Res.* **15**, 1250 (1979).
69. R. E. Dickinson, A. Henderson-Sellers, P. J. Kennedy, M. F. Wilson, *Biosphere-Atmosphere Transfer Scheme* (National Technical Information Service, Springfield, VA, 1986); P. J. Sellers, Y. Mintz, Y. C. Sud, A. Dalcher, *J. Atmos. Sci.* **43**, 505 (1986); D. Pollard and S. L. Thompson, *Global Planet. Change*, in press.
70. If there were, for example, a radiative cooling over land associated with regional sulfate aerosol increases as calculated by Kiehl and Briegleb (*54*) from the sulfate maps of Langner and Rodhe (*60*), then this would both reduce surface temperature and net radiation. These, in both reality and the more advanced biophysical parameterizations, would reduce evapotranspiration and, presumably, local absolute atmospheric humidity, thereby leading to a positive feedback that could amplify the local surface temperature decreases. Likewise, over land masses warmed by greenhouse gases or over the oceans, the large-scale positive water vapor–greenhouse effect feedback that is well described by Ramanathan (*61*) would also be in operation, even though the land and oceanic components might have very different time scales of response to radiative forcing.
71. P. D. Jones, T. M. L. Wigley, C. K. Folland, D. E. Parker, *Clim. Monit.* **16**, 175 (1988).
72. H. W. Ellsaesser, *Atmos. Environ.* **18**, 431 (1984).
73. R. S. Lindzen, *Am. Meteorol. Soc.* **77**, 288 (1990).
74. S. H. Schneider, *Bull. Am. Meteorol. Soc.* **72**, 1009 (1991); D. Rind *et al.*, *Nature* **349**, 500 (1991).
75. R. A. Kerr, *Science* **249**, 481 (1990); T. Wicker, *New York Times*, 24 October 1991, p. A25; A. Gore, *Earth in the Balance: Ecology and the Human Spirit* (Houghton Mifflin, Boston, 1992).
76. D. Z. Sun and R. S. Lindzen, *J. Atmos. Sci.* **50**, 1643 (1993).
77. A. K. Betts, *Bull. Am. Meteorol. Soc.* **71**, 1465 (1990).
78. By "globally averaged residual effects," I refer to nonlinear effects such as ice-albedo-temperature feedbacks. For example, if somehow there were a net radiative forcing of 1 W m^{-2} between 30°N and 30°S (one-half the global surface area) and a net radiative forcing of −1 W m^{-2} between 90°S and 30°S, and 90°N and 30°N, then it is quite possible that the globally averaged temperature response to this zero globally averaged net radiative forcing would nonetheless have a nonzero residual global average cooling, because the positive ice-albedo-temperature feedback operates more strongly in cooler zones than in the zone from 30°N to 30°S. The Kiehl-Briegleb results also imply that it would not be possible to perfectly offset the climatic effects of increased greenhouse gases by, for example, deliberately spreading aerosol particles in the stratosphere. This is because those high-altitude particles would spread fairly uniformly around latitude zones, thus reflecting sunlight in zonal patterns; however, the infrared radiative forcing for greenhouse gases is regionally heterogeneous owing to the nonuniform distribution of water vapor and high clouds. In other words, even if one could "geoengineer" an exact cancellation of the inadvertent globally averaged greenhouse radiative heating with a deliberate injection of stratospheric particle cooling, uneven regional heating-cooling patterns could still have significant regional climatic impacts through residual effects or teleconnections.
79. Although breakthroughs in computing technology or model architecture (for example, highly parallel systems) may hold some promise for rapid improvements, I suspect that ensembles of high-resolution, coupled two-century ESM runs are yet decades away.
80. S. H. Schneider, L. O. Mearns, P. Gleick, in *Global Warming and Biological Diversity*, P. Waggoner, Ed. (Yale Univ. Press, New Haven, CT, 1992), chap. 4, table 4.1.
81. It is my strong belief that physical, biological, and chemical subsystem models need to be coupled and data sets assembled for their validation, even if the scientific understanding at the level of individual subsystems has not yet been worked out to the satisfaction of the disciplinarians who work on those subsystems or on related processes at small scales. See, for example, T. L. Root and S. H. Schneider, *Conserv. Biol.* **7**, 256 (1993); J. R. Ehleringer and C. B. Field, Eds., *Scaling Physiological Processes: Leaf to Globe* (Academic Press, New York, 1993); and S. Levin, *Ecology* **73**, 1943 (1992).
82. Time series of tree ring growth [for example, V. C. LaMarche, *Nature* **276**, 334 (1978)] or glacial moraine movements [for example, G. H. Denton and W. Karlen, *Quat. Res.* **3**, 155 (1973)] can be used to estimate the likelihood of century-long global temperature trends, even though caution is needed because such proxies are not direct temperature measurements and are not globally distributed. But they are long-term time series.
83. My detailed views on these value judgments are explained in S. H. Schneider, *Global Warming: Are We Entering the Greenhouse Century?* (Vintage, New York, 1990).
84. S. B. Idso and A. J. Brazel, *Science* **198**, 731 (1977); R. E. Newell and T. G. Dopplick, *J. Appl. Meteorol.* **18**, 822 (1979).
85. I thank C. Covey, W. Kellogg, J. Kiehl, V. Ramanathan, and S. Warren for helpful comments on early draft manuscripts and J. Kiehl once more for providing the July net radiative forcing maps that have not previously been published. The National Center for Atmospheric Research is sponsored by NSF. The views expressed in this article are those of the author and do not necessarily reflect those of NSF.