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The Missing Data on Global Climate Change

A pair of small, inexpensive satellites could help answer pressing questions about projected warming trends.

Governments worldwide have suddenly realized that they face an issue unprecedented in the history of science and technology: the anthropogenic greenhouse effect. Will gases spewed into the atmosphere by modern civilization cause large global climate changes, threatening the natural biosphere as well as civilization itself? The issue is urgent because the long lifetime of these gases in the atmosphere and the slow response time of the climate system mean that we are committing ourselves and our children to live with whatever changes do occur as a result of our actions today.

Scientific warnings have generated rancorous political debate owing to the presumed costs of curtailing greenhouse-gas emissions. And the debate is fueled by scientific uncertainties. Are climate changes already occurring? Are they caused by the greenhouse effect? What climate impacts are likely in coming years and decades? Until those questions can be answered, legislators are unlikely to agree on a policy response. Indeed, policymakers cannot even weigh the various options rationally until the climate system is better understood, and that, in turn, depends on the availability of comprehensive observations of global climate change.

In the following discussion we summarize the measurements that are needed to characterize changes in the Earth's climate. Much of the data is already being acquired by operational satellites and ground stations. Several important parameters are not being measured, however, and these omissions will persist until the end of the decade, when the National Aeronautics and Space Administration (NASA) plans to include the necessary data-gathering instruments in the Earth Observing System (EOS), a set of large polar-orbiting platforms. The urgency to answer questions about climate change compels us to ask whether the missing data can be collected more quickly. Specifically, can the instruments be placed on smaller satellites that can be launched sooner?

Our principal conclusion is that the most crucial unmeasured climate quantities could be obtained by a pair of inexpensive small satellites. The proposed satellites would allow climate data to be obtained sooner than from the large EOS platforms, improve the

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quality of the climate data, and reduce the requirements and complexity of the EOS platforms. Thus the overall results can be improved while we avoid the dangers of having all our eggs in one large basket.

Climate analysis

Greenhouse gases are only one of the mechanisms causing long-term climate change. And, in addition to "forced" climate changes, there are internal chaotic fluctuations of the climate system that occur without forcing. A climate-observing strategy must include not only detection of climate change, but collection of data that allows us to distinguish among anthropogenic causes and between these forced changes and natural climate fluctuations.

Thus climate observations must include the principal external climate-forcing mechanisms and internal climate feedbacks, as well as the key indicators or diagnostics of climate change. Data on climate forcings is needed to help determine the cause of any observed climate change. Climate feedbacks must be known before we can predict how large future climate changes will be. Climate diagnostics must be monitored with high accuracy over a long enough time to define climate variability and detect any climate trends.

Some climate forcings, feedbacks, and diagnostics are presently measured by operational satellites and ground stations. Others are not. In this section we will elaborate on each of the measurement types and address in greater detail the parameters that are being neglected. Table 1 summarizes the discussion.

Climate forcings. A climate forcing is a change imposed on the planetary energy balance that alters global temperature. Although the term is sometimes used to refer to the transient heating associated with internal climate fluctuations, such as regional cloud cover changes or snowfall, we restrict "forcings" to describe anthropogenic or externally imposed changes.

A climate forcing is measured by the change in the heating rate of the Earth in watts per square meter (W/m^2). For example, the increases of the greenhouse gases carbon dioxide (CO_2), chlorofluorocarbons (CFCs), methane (CH_4), and nitrous oxide (N_2O) that have occurred since the International Geophysical Year in 1958 cause a heating change of 1.1 W/m^2. That greenhouse heating is equivalent to placing one of the miniature bulbs of a Christmas tree string above every square meter of the Earth's surface. The accumulated increases in such greenhouse gases since the Industrial Revolution began in 1800 cause a heating change of more than 2 W/m^2 by decreasing the infrared radiation emitted to space—an amount equivalent to increasing by one percent the solar radiation absorbed by the Earth.

The heating changes caused by increases in those four gases can be calculated because accurate long-term data are available for their atmospheric abundances. All four are relatively well mixed in the troposphere (the lowest 10 kilometers of the atmosphere), so the measurements recorded by a few ground stations can provide a good record. But two important greenhouse gases are not being measured adequately: ozone (O_3) in the upper troposphere and water vapor in the stratosphere (the region between 10 and 50 kilometers in altitude).

Upper tropospheric ozone is so variable and poorly measured that it is impossible to say whether its long-term changes cause a net warming or cooling. Water vapor in the stratosphere is probably increasing because of oxidation of an increasing abundance of methane, but global measurements of water vapor trends have not been made. The vertical profiles of both tropospheric ozone and stratospheric water vapor must be monitored globally to assess total greenhouse climate forcing.

The greatest anthropogenic climate forcing outside of the greenhouse gases is the buildup of tropospheric aerosols. Aerosols are small solid or liquid droplets in the air that, in sufficient amounts, cause a visible haze or smog. The dominant aerosols are sulfates, which form from sulfur dioxide (SO_2) released by the burning of coal and oil as well as from natural processes.

The overall impact of accumulating tropospheric aerosols appears to be increased reflection of sunlight by the Earth, which results in a cooling effect. Indeed, some scientists have argued that increasing aerosols will send the Earth into an ice age! About 25 to 50 percent of the aerosols in the atmosphere may be anthropogenic in origin. That percentage corresponds to a mean cooling change of between 0.5 and 1.5 W/m^2. Empirical evidence of a warming Earth implies that total aerosol cooling is less than greenhouse heating, but it is impossible to determine the net climate

TABLE 1

Principal Global Climate Forcings, Feedbacks, and Diagnostics

	Existing Source	Proposed Source
Climate Forcings		
Greenhouse gases		
CO_2	G	
CFCs	G	
CH_4	G	
N_2O	G	
O_3 (profile)	–	SAGE
stratospheric H_2O	–	SAGE
Aerosols		
tropospheric	–	EOSP
stratospheric	–	SAGE
Solar Irradiance	X	
Surface Reflectivity	O (poorly calibrated)	EOSP
Climate Feedbacks		
Clouds		
cover	O, W	
height (temperature)	O	
optical depth	O	
particle size	–	EOSP
water phase	–	EOSP
Tropospheric H_2O (profile)	O, W (lower troposphere)	SAGE
Sea Ice Cover	O	
Snow Cover/Vegetation	O	
Ocean Heat Exchange (vertical mixing & horizontal divergence)	S, X	
Climate Diagnostics		
Radiation Budget	–	ERB
Temperature		
upper air	W, O	
surface air	W	
ground	O	
sea surface	S, O	
ocean, internal	S	
Precipitation	W, O, X	

Data source key: O = operational satellite system, X = experimental satellites (e.g., TRMM), W = operational weather station network, G = other ground stations and aircraft, S = ships and buoys. SAGE = Stratospheric Aerosol and Gas Experiment. EOSP = Earth Observing Scanning Polarimeter. ERB = Earth Radiation Budget scanner.

Note: Climate parameters that have more than one role—for example, forcing and feedback—are listed under their dominant influence.

forcing as long as the aerosol component of the atmosphere is unknown.

Anthropogenic cloud changes, which may result from urban pollution, power plant emissions, or aircraft contrails, are also a climate forcing. This cloud forcing should be identifiable from observing spatial cloud patterns in conjunction with data for global aerosol distributions. For these studies, as discussed below (under climate feedbacks), global cloud measurements need to be enhanced to include information on the cloud microphysics, specifically the cloud particle size and phase (liquid or ice).

Stratospheric aerosols are also a major forcing factor. Unlike their lower-atmosphere counterparts, the stratospheric aerosols arise mostly from the episodic injection of SO_2 and dust high into the atmosphere by large volcanos. There is some evidence of a slow increase of the background (nonvolcanic) stratospheric aerosol amount, which hints at an anthropogenic influence. Although instruments on various spacecraft have measured the stratospheric aerosols in polar regions during the past decade, long-term global data are still sorely needed.

The sun's irradiance is another obvious candidate for climate forcing. During the past decade spacecraft took precise measurements of solar irradiance; these observations showed that the sun dimmed by 0.1 percent between 1979 and 1986, with a subsequent partial recovery. The 0.1 percent dimming represented a heating decrease of about 0.25 W/m^2. Since long-term solar behavior has not been characterized, accurate monitoring must be maintained. NASA plans to continue flying precise solar monitors on satellites of opportunity. This strategy will work as long as it is designed to keep two instruments in orbit, thus allowing cross-checking and continuity of calibration when one instrument fails and must be replaced. Continued attention to the progress of solar monitoring plans is required.

Finally, changes in the Earth's surface reflectivity due to deforestation or desertification may also be significant climate forcings. The impacts that result from such forcings are probably restricted to the regions where surface changes have occurred; however, such changes are encompassing wider and wider areas. Operational meteorological satellites currently measure the Earth's surface reflectivity, but their instruments are not calibrated well enough to provide reliable long-term data.

In summary, although certain climate forcings are well observed, it is essential that all significant forcings be measured together to allow cause-and-effect assessment of any observed climate changes. The key quantities that are not being monitored at present are upper tropospheric ozone, stratospheric water vapor, and aerosols in both the troposphere and the stratosphere. In addition, the satellite instruments that measure surface reflectivity must be calibrated better to be useful for long-term monitoring.

Climate feedbacks. Climate feedbacks are internal reactions of the climate system to natural or anthropogenic climate change. Positive feedbacks amplify the climate change; negative feedbacks diminish it. A negative feedback cannot reverse the sense of a climate change because the feedback is driven by the climate change. But if a negative feedback were strong enough, it could reduce the climate change to negligible proportions. Indeed, scenarios involving negative feedbacks have been used as an argument for delaying policy actions on greenhouse gases. It is essential that climate feedbacks be assessed accurately in order to evaluate the sensitivity of the climate to forcings.

Clouds are among the most enigmatic of feedback factors. How will clouds change with increased greenhouse warming? Higher surface temperature causes increased evaporation which, it can be argued, may increase cloud cover. And since most clouds cool the Earth, increased clouds would act as a negative feedback, reducing the greenhouse warming. But most global climate models suggest just the opposite outcome: Increased evaporation leads mainly to more vigorous moist convection and thunderstorms over a very small portion of the Earth's surface; for the rest of the planet, there is increased drying of air by subsidence, thus reduced cloud cover, and a positive feedback.

Other, as-yet-unspecified, cloud feedback effects are possible. But scientists will not be able to predict them with confidence until they have a record of global cloud measurements to study in conjunction with changes in other climate parameters, which can then serve as a basis for fine-tuning their models. Operational satellites are currently being used to acquire a global cloud climatology, and this surveillance needs to be continued through the 1990s. But what is missing is data on cloud microphysics, which are important because the size and phase of cloud droplets affect the reflection and absorption of solar and terrestrial radiation.

Water vapor in the lower atmosphere causes a positive climate feedback, because warmer air holds more vapor and water vapor is a major greenhouse gas. However, several processes (such as large-scale atmospheric circulation and the injection of water by thunderstorms) influence the atmospheric humidity profile in different ways, so the magnitude of the water vapor feedback is uncertain. Reliable evaluation of the climate feedback resulting from water vapor requires monitoring water vapor in conjunction with climate changes so that correlations between the two can be identified. In particular, the scarcity of water vapor data in the upper troposphere must be redressed.

Sea ice could provide a strong regional climate feedback as well. Increased temperatures melt the ice and result in increased absorption of solar energy by the ocean, which is darker than the ice. The absence of sea ice in the winter also strongly enhances heat transfer from the ocean to the atmosphere. Microwave measurements from operational weather satellites offer a good record of sea-ice patterns since the early 1970s, and continuation of those measurements will suffice.

Snow and vegetation cover may also be affected by climate change. In turn, these changes of land surface characteristics alter the exchanges of energy, water, and trace gases with the atmosphere. The snow and vegetation variations can be monitored from the changes in surface reflectivity measured by instruments on operational weather satellites.

Finally, ocean changes could provide a large climate feedback, particularly on regional scales. It is expected that the rate of heat transport by the ocean will vary in response to climate change at the ocean surface. Extensive measurements from ships and buoys are planned to begin in the early 1990s under the auspices of the World Ocean Circulation Experiment (WOCE). But WOCE measurements are scheduled to end by 1995. They need to be extended in time if they are to monitor long-term ocean change. WOCE will also include precise altimetry of the ocean surface measured from a satellite; this technique can detect small changes in the patterns of ocean density and may provide an effective index of global ocean change. The altimetry should be continued in the latter 1990s from an appropriate satellite platform.

The small satellites and large polar platforms are complementary rather than mutually exclusive.

In summary, although data on many climate feedbacks are already obtained by operational satellites, better independent calibration of the satellite instruments should be instituted. In addition, it is necessary to have global measurements of upper tropospheric water vapor as well as detailed cloud information, particularly cloud water phase and particle size. And the collection of world ocean data to be initiated by WOCE needs to be continued at least throughout the 1990s.

Climate diagnostics. Climate-change diagnostics are required both for determining the existence and nature of climate changes and for analyzing the causes. Of paramount importance for understanding the climate system are the global energy and water cycles, which include the driving forces and principal mechanisms of the climate system. Moreover, the energy and water cycles include the climate parameters of greatest practical importance to man: temperature and water supply.

The energy cycle can be analyzed effectively by measuring the radiation (Earth's only means of energy exchange with space) entering and leaving at the top of the atmosphere. Satellite measurements of the radiation budget can be used to diagnose both forcings and feedbacks in regional as well as global climate. And by analyzing data on aerosols and clouds in conjunction with changes in the radiation balance, we can test the climate models for accuracy.

In the past five years, the radiation balance has been measured with the instruments of the Earth Radiation Budget Experiment (ERBE). However, the scanner instruments, which provided most of the relevant data, are no longer functioning. So it is important to have new instruments during the 1990s, when global climate changes are anticipated and other climate parameters are being monitored. The Europeans plan to launch radiation-budget satellite SCARAB in the early 1990s; the United States should plan to launch new instruments by the mid-1990s.

Surface air temperature responds to changes in the planet's energy balance and provides a simple measure of climate change. It needs to be measured in a variety of ways—satellites, surface stations, and weather balloons—to ensure global coverage, accurate calibration, and comparability with historical records.

Internal ocean temperature is a key climate diagnostic because it serves to integrate the effect of surface forcing over time and because the amount of heat stored in the ocean during long-term climate change provides an indication of climate sensitivity. Measurements along two vertical cross sections of the North Atlantic Ocean in 1958 and in 1981 show evidence of internal temperature change during that period. The change was, on average, an increase, but the interpretation is unclear because of the limited coverage. Temperature surveillance included in WOCE could provide long-term global coverage of ocean temperature, but again, it must be continued throughout and beyond the 1990s.

A new technique proposed by Walter Munk of Scripps Institution of Oceanography shows promise for simplifying the ocean monitoring task. Based on the fact that the speed of sound in water depends on the water's temperature, changes in long-path acoustic travel times would indicate temperature fluctuations and allow inference of ocean warming within several years. The necessary data could be obtained using underwater sonic sources at a small number of islands in the southern oceans that would provide sound-wave paths to a large number of coastal and island locations in both hemispheres.

Precipitation, like temperature, is a crucial diagnostic. Not only is water supply vital to human existence, but precipitation also determines the distribution of latent heat release in the atmosphere, which is a principal engine for atmospheric motions. But precipitation is particularly difficult to measure because of its large spatial and temporal variability. Currently, precipitation is monitored at spot locations on land by surface weather stations, and crude data over oceans are obtained by passive microwave measurements from operational satellites. Tests of microwave and radar measurements from satellites are planned for a Tropical Rainfall Measuring Mission (TRMM) in the middle 1990s. TRMM will provide rainfall data for a crucial part of the climate system; however, rainfall measurements must be extended to global coverage. TRMM may be able to aid that objective by testing methods of inferring rainfall from the infrared and visible images that cover the globe.

In summary, there is an urgent need to restore and maintain global radiation-budget measurements, which are the principal diagnostic of the Earth's energy cycle. The ocean measurements planned for WOCE should be extended, and Munk's acoustic technique to monitor ocean temperature should be implemented. Finally, rainfall data needs to be collected globally.

The climate-change satellites

The preceding discussion highlights some of the elements that are essential for the analysis of climate change; they include long-term calibrated data with global coverage. High-frequency sampling, preferably several times per day, is also needed to gather meaningful statistics on rapid atmospheric processes, particularly those that affect clouds, radiation, and precipitation.

As we have pointed out, much of the required data is already being obtained by weather stations and other ground measurements and by operational weather satellites. Other portions of the required data will be provided by planned projects and their extensions, such as WOCE and TRMM. But several large data gaps remain, which, if unfilled, would make it impossible to interpret climate changes in the 1990s.

The exciting conclusion that emerges from our survey of climate observations is that all of the essential parameters that are not included in existing or imminent projects could be measured by just three instruments on two satellites (CLIMSATs). In the remainder of this section we describe the three instruments and estimate their cost. It is also worth noting, in light of the need for independent calibration of existing satellite instruments, that the measurements from the CLIMSATs also could be used to improve the value of the weather satellite data for climate studies.

Upper-atmosphere aerosol and gas monitor. The vertical profiles of water vapor, ozone, and aerosols can all be measured at high resolution with the Stratospheric Aerosol and Gas Experiment (SAGE), which has been tested with observations from space during the 1980s. SAGE views the sun as it rises or sets at the Earth's horizon (and is thus eclipsed or "occulted") so that it can measure what happens to sunlight as it passes through the atmosphere at various altitudes down to the level at which clouds obscure the line of sight. Because we know what wavelengths of light are absorbed and scattered by water vapor, ozone, and aerosols, we can calculate the concentrations of these components by comparing the observed spectrum of light that has passed through a vertical cross section of the atmosphere with the spectrum of direct sunlight.

The high absolute accuracy of SAGE data is crucial for climate monitoring. And SAGE is particularly well suited to climate studies because it is self-calibrating: it compares its daily observations of the occulted sun with same-day measurements of direct sunlight. Moreover, a baseline of data for the 1980s has already been established by earlier SAGE instruments.

The principal deficiency of SAGE has been its poor spatial coverage; it observes only two solar occultations per orbit. In the future, however, SAGE instruments will also observe lunar occultations, thus increasing the number of samples. If this instrument is included on both a polar orbiter and an orbiter inclined at about 57 degrees, it will be able to obtain adequate global coverage for long-term climatological monitoring.

Tropospheric aerosol and cloud monitor. The most uncertain climate forcing is that due to changing tropospheric aerosols. The principal measurement needed is of the aerosols themselves; but, as we have pointed out, it is also important to measure cloud properties, such as particle size and water phase, that are most directly affected by aerosol changes. These quantities can be measured by the Earth-Observing Scanning Polarimeter (EOSP), an instrument with a long heritage from planetary missions.

EOSP measures the radiance and polarization of sunlight reflected by the earth in many spectral bands in the visible and near-infrared region. These data are used to derive the amount and extent of atmospheric aerosols as well as several cloud properties, including the atmospheric pressure, particle size, and water phase at the cloud tops.

The small climate satellites would ensure that the key parameters were covered, and covered soon.

EOSP is particularly relevant to climate studies because it maintains accurately calibrated radiances by way of internal and external calibration sources. Since it will have several channels in common with the scanning radiometers on operational weather satellites, it can also be used to help calibrate the operational data so it can be used to infer factors such as cloud properties and surface reflectivity, thus making that information more useful for climate studies.

Earth radiation budget. The planetary energy budget at the top of the atmosphere is a vital climate diagnostic. Its measurements have a long history, beginning with the first launch of meteorological satellites in 1957. More recent generations of instruments flew on the NIMBUS satellites and operational weather satellites in polar orbit throughout the 1970s and 1980s, and on the Earth Radiation Budget Experiment (ERBE) satellite, launched in 1984, in an orbit inclined 57 degrees from the equator. Since the demise of the last scanner instrument in early 1990, however, only limited measurements of the radiation budget have been possible.

The ERBE scanner measures quantities that have large variations on all time scales, from hours to years. Thus at least two satellites are required to distinguish seasonal and weather variations from diurnal variations: one in a 57-degree inclined orbit, and one in a sun-synchronous polar orbit. Measurements are planned for the EOS platforms and the U.S. Space Station *Freedom*, but we believe that ERBE should be included on the proposed small climate satellites to ensure that radiation budget data are available in the same time frame as all the other climate forcing and feedback data.

Preliminary cost estimate. Although a full engineering study is necessary to precisely determine costs, preliminary analysis and comparisons with similar missions make a rough estimate possible. Three sets of the three instruments (one reserve set as insurance against launch or in-orbit failure) would cost about $100 million. Three satellites would cost less than $150 million. Launching the two satellites, together with other payloads aboard a U.S. Delta rocket or alone on a smaller foreign launch vehicle, would cost $25 million per launch. Five years of mission operations and data analysis would cost on the order of $50 million. Thus the total bill would be about $350 million, or $35 million a year over the life of the project. The U.S. share could be cut by perhaps $100 million if other countries were willing to participate, as is now commonly the case in earth science missions.

What about Mission to Planet Earth?

The CLIMSAT proposal must be viewed in the context of Mission to Planet Earth, NASA's proposed wide-ranging environmental research program. MPE's broad goal is to obtain a comprehensive understanding of the Earth system and how it evolves on all time scales, with a focus on the next century. Many earth-science disciplines are included, from solid-earth geophysics to solar- terrestrial relations; climate, biogeochemistry, ecology, and human interactions also figure prominently. The observational network for MPE is expected to include satellites in polar, inclined, and geostationary orbits.

So far, most attention has centered on the EOS subsystem of the mission—involving two large U.S. polar platforms, as well as a European platform and a Japanese platform. The EOS platforms can accommodate large instruments that observe with high spatial resolution and high spectral resolution and are thus well suited for earth-system process studies. And because the platforms can house numerous instruments, they make possible simultaneous observations of many parameters—an important aid to process studies.

Thus, even with the CLIMSATs in place, the EOS platforms would provide additional valuable climate data. Moreover, even though the principal climate forcings, feedbacks, and diagnostics have been recognized for many years, we cannot be certain that others will not emerge from further research. Thus the broad-based observations of the EOS platforms will provide a valuable database for studying new issues and scientific ideas.

But because the EOS platforms are expected to monitor so many variables, they cannot be optimized for them all. The CLIMSATs, with tested technology, modest expense, and optimal orbits, would ensure that the key climate parameters were covered, and covered soon. They present a clear "win-win" situation, providing improved climate data while allowing the polar platform to be optimized for other global-change observations.

There are several additional advantages to use of separate satellites. They alleviate the danger of losing all the data in a launch or subsystem failure. Also, smaller and less complex spacecraft are not as prone to schedule slips, which can drive up costs and leave decisionmakers without the needed climate information. And the small satellites can have shorter time intervals between design and launch, making it possible to include timely engineering and scientific advances.

The proposed CLIMSAT underlines the need for support of Earth Probes, NASA's small-satellite program. The administration's $25-million 1991 budget request for Earth Probes will force delays in several missions, including the TRMM mission that will supply needed precipitation data. The entire small-satellite program deserves substantially increased funding.

We are aware that our advocacy of a small-satellite mission inevitably leaves the impression that we are undermining support for the larger EOS mission. But we see the small satellites and polar platforms as complementary rather than mutually exclusive. There is good justification for both systems.

The real danger, in our opinion, is that essential climate measurements and accompanying research will be held hostage to the rate of progress of the much larger EOS program, which is still only one component of Mission to Plant Earth. The urgency of the global climate issue demands that we take the fastest and most reliable route to obtaining needed climate data.

Recommended reading

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