LOW-COST LONG-TERM MONITORING OF GLOBAL CLIMATE FORCINGS AND FEEDBACKS

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Abstract. We describe the rationale for long-term monitoring of global climate forcings and radiative feedbacks as a contribution to interpretation of long-term global temperature change. Our discussion is based on a more detailed study and workshop report (Hansen *et al.*, 1993b). We focus on the potential contribution of a proposed series of inexpensive small satellites, but we discuss also the need for complementary climate process studies and ground-based measurements. Some of these measurements could be made inexpensively by students, providing both valuable climate data and science educational experience.

Introduction

Climate varies on all time scales, and there are many aspects of climate change with practical importance. Without prejudice to other issues, this paper focuses on global temperature change on time scales from a year to several decades, a topic of societal concern because of the suspected role of human-made greenhouse gases in causing long-term change. We call attention to the need for high precision monitoring of all significant global climate forcings as an essential requirement for interpretation of global temperature changes. Without such data, which are not covered adequately by current monitoring plans, uncertainty about the causes and implications of observed climate change will persist indefinitely, and it will be much harder to decide on a prudent environmental policy.

Quantitative knowledge of all global climate forcings, natural and human-made, is essential to national and global policymakers. Environmental and energy policies, for example, will be influenced by the degree to which greenhouse gases and fine particles in the lower atmosphere, produced by use of fossil fuels and by biomass burning, are judged to influence global climate. Even after policy decisions are made, monitoring of the climate forcings to a precision that accurately defines their changes is necessary in order to judge the effectiveness of the policies.

In this paper we discuss the principal global climate forcings and radiative feedbacks. We show that many of these quantities could be observed with the required high precision, global coverage, and time-space sampling by a pair of small, inexpensive satellites. We also underline the need to observe other climate forcings and radiative feedbacks not included on the specific small-satellite we propose, called Climsat, as well as the need for complementary field projects and measurements from surface stations. Together with existing observations, these measurements will

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strongly constrain interpretation of observed global temperature change and permit quantitative comparison of climate forcing mechanisms which presently involve substantial uncertainty. We recognize that the proposed Climsat measurements also have application to regional climate phenomena of much practical interest, but our strategy is to focus on global climate change, using the needs for interpretation of global temperature change to define measurement requirements.

We assume that Climsat would be carried out within the context of, and as one contribution to, a comprehensive global observing system. Climsat thus is meant to be a key addition to existing and planned observing systems, including the international Global Climate Observing System and the Global Ocean Observing system. Other fundamental climate diagnostics, such as precipitation and ocean parameters, need to be measured by existing and new experimental systems, and by their follow-on programs. It is also important that the meteorological observing system of NOAA be upgraded to enhance its effectiveness for climate monitoring. NASA's Earth Observing System can provide detailed measurements important to the study of many climate processes. DOE's existing and planned Atmospheric Radiation Measurements ground sites could effectively complement Climsat observations, as could appropriate observations by high school students in the planned GLOBE program.

Forcings and Feedbacks

Global temperature has increased significantly during the past century (IPCC, 1990; Hansen and Lebedeff, 1987; Jones *et al.*, 1986). Understanding the causes of observed global temperature change is impossible in the absence of adequate monitoring of changes in global climate forcings and radiative feedbacks. We define climate forcings as changes *imposed* on the Earth's energy balance which work to alter global temperature, for example, a change of incoming solar radiation or a man-made change of atmospheric composition. Radiative feedbacks are responses to climate change, such as altered cloud properties or sea ice cover, which may magnify or diminish the initial climate change.

Monitoring of global climate forcings and feedbacks, if sufficiently precise and long-term, can provide a *very strong constraint* on interpretation of observed temperature change. Such monitoring is essential to eliminate uncertainties about the relative importance of various climate change mechanisms including tropospheric sulfate aerosols from burning of coal and oil (Charlson *et al.*, 1992), smoke from slash and burn agriculture (Penner *et al.*, 1992), changes of solar irradiance (Friis-Christensen and Lassen, 1991), changes of several greenhouse gases, and many other mechanisms.

The considerable variability of observed temperature, together with evidence that a substantial portion of this variability is unforced (Barnett *et al.*, 1992; Manabe *et al.*, 1990; Hansen *et al.*, 1988; Lorenz, 1963), indicates that observations of climate forcings and feedbacks must be continued for decades. Since the climate system responds to the time integral of the forcing, a further requirement is that the observations be carried out continuously.

However, precise observations of forcings and feedbacks will also be able to provide valuable conclusions on shorter time scales. For example, knowledge of the climate forcing by increasing CFCs relative to the forcing by changing ozone is important to policymakers, as is information on the forcing by CO_2 relative to the forcing by sulfate aerosols. It will also be possible to obtain valuable tests of climate models on short time scales, if there is precise monitoring of all forcings and feedbacks during and after events such as large volcanic eruption or an El Niño.

Greenhouse gases. The measured increase of homogeneously mixed greenhouse gases since the beginning of the industrial revolution causes a climate forcing of about 2 W/m^2 (IPCC, 1992; Hansen and Lacis, 1990; Dickinson and Cicerone, 1986; Ramanathan *et al.*, 1985; Wang *et al.*, 1976), as illustrated in Figure 1. Although a host of chemical species, e.g., NO_x, CO and OH, requires monitoring for the purpose of understanding greenhouse gas trends and predicting future changes, the well mixed greenhouse gases are measured accurately already. However, there is major uncertainty about the total anthropogenic greenhouse forcing, especially because of uncertain changes of the ozone profile (IPCC, 1992; Ramaswamy *et al.*, 1992; Lacis *et al.*, 1990). Stratospheric water vapor also may be increasing not just because of oxidation of increasing methane (Ellsaesser, 1983; Le Texier *et al.*, 1988), but also other as-yet-not-understood mechanisms (Oltmans and Hofmann, 1995), so, in the absence of adequate monitoring, its net climate forcing is very uncertain.

Climate forcing due to ozone change is complicated because ozone influences both solar heating of the Earth's surface and the greenhouse effect. Both of these mechanisms influence surface temperature, but their relative importance depends on the altitude of the ozone change. Figure 2 illustrates the equilibrium response of a GCM to specified ozone changes: (a) Ozone loss in the upper stratosphere warms the Earth's surface, because of increased ultraviolet heating of the troposphere; (b) Added ozone in the troposphere warms the surface moderately; (c) Ozone loss in the tropopause region causes a strong cooling because the low temperature at the tropopause maximizes the ozone's greenhouse effect; (d) Coincidentally, removal of all ozone causes only a moderate surface cooling.

The ozone changes that had been predicted for many years on the basis of homogeneous (gas phase) chemistry models included upper stratospheric ozone loss and tropospheric ozone increase. Both of those ozone changes would cause surface heating. But limited ozone measurements in the 1970s (Tiao *et al.*, 1986; Reinsel *et al.*, 1984) suggested the possibility that upper tropospheric ozone and lower stratospheric ozone may be decreasing. Discovery of the Antarctic ozone hole in the 1980s (Farman *et al.*, 1985) and analysis of the mechanisms involved in the ozone depletion led to the realization of the effectiveness of heterogeneous loss

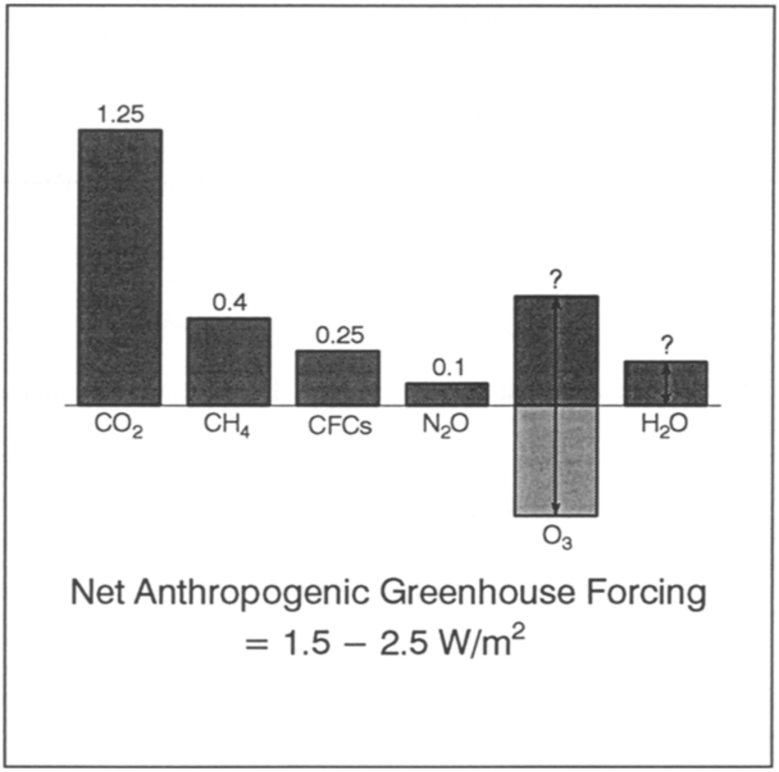

Fig. 1. Anthropogenic greenhouse climate forcings (W/m^2) due to measured or estimated trace gas changes between 1850 and 1990. The forcing is calculated as the change in net radiative flux at the tropopause caused by the change in atmospheric composition (Hansen and Lacis, 1990).

processes in the 15–25 km region (WMO, 1990). Satellite data for the 1980s (Stolarski *et al.*, 1991; McCormick *et al.*, 1992) have shown that the lower stratospheric ozone loss is not confined to the Antarctic.

It will not be possible to accurately evaluate the total anthropogenic greenhouse effect unless ozone change is monitored as a function of altitude, latitude and season. Useful stratospheric ozone profile data are presently supplied by the SAGE II instrument on the ERBS satellite, which is over 10 years old. As discussed below, this data record could be extended and enhanced by flight of a proposed improved version of the instrument (SAGE III) with greater sensitivity, higher spectral resolution, and increased spatial sampling, as one contribution to more comprehensive ozone monitoring.

Aerosols. Perhaps the greatest uncertainty in climate forcing is that due to tropospheric aerosols (Charlson *et al.*, 1992). Aerosols cause a direct climate forcing, by reflecting sunlight to space and absorbing solar and terrestrial radiation in the atmospheric column, and an indirect climate forcing, by altering cloud properties. Existence of the latter effect is supported by satellite observations of increased

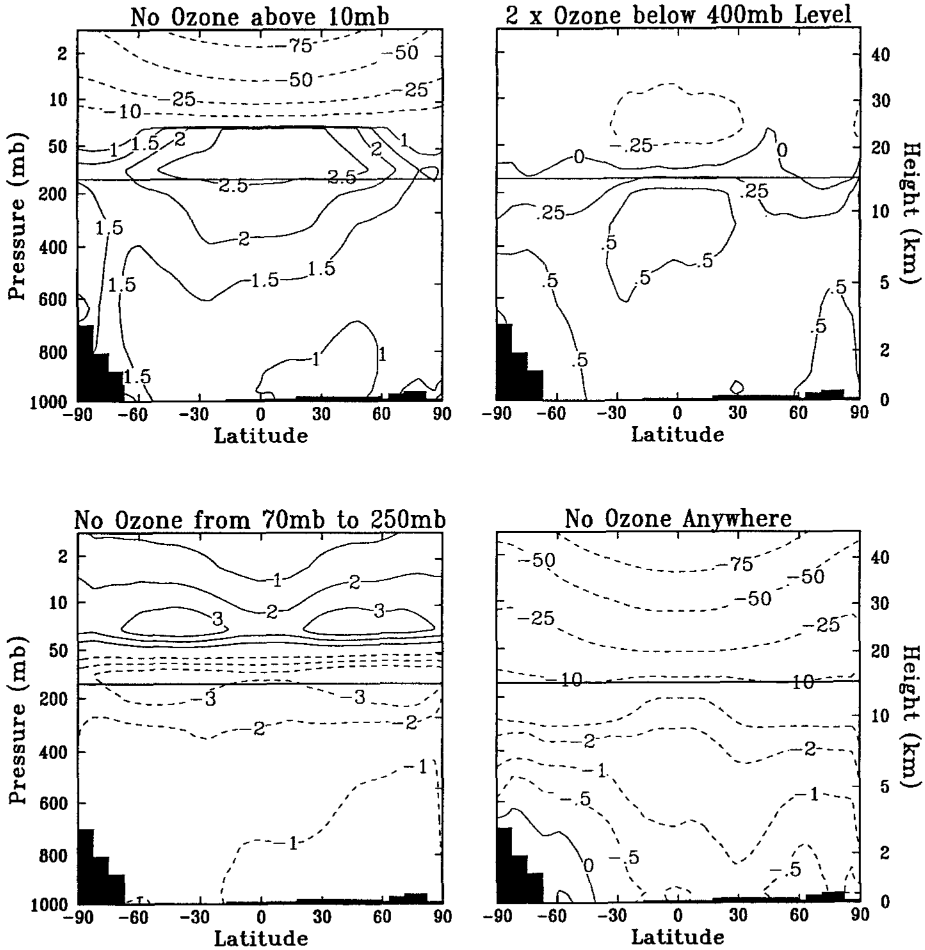

Fig. 2. Zonal mean equilibrium temperature change (°C) estimated for several arbitrary changes of the ozone distribution. Results were obtained from 100 year runs of the GISS GCM.

cloud brightness in ship wakes (Coakley *et al.*, 1987), satellite observations of land-ocean and hemispheric contrasts of cloud droplet sizes (Han *et al.*, 1994), and *in situ* data concerning the influence of aerosol condensation nuclei on clouds (Radke *et al.*, 1989). Sulfate aerosols originating in fossil fuel burning may produce a global climate forcing of order –1 W/m^2 (Charlson *et al.*, 1991), and aerosols from biomass burning could conceivably produce a comparable forcing (Penner *et al.*, 1992). Wind-blown dust, influenced by anthropogenic activities, has long been suspected of being an important forcing on some regional climates (Tanre *et al.*, 1984; Joseph, 1984; Coakley and Cess, 1985; Tegen and Fung, 1994). It has also been suggested (Jensen and Toon, 1992; Sassen, 1992) that volcanic aerosols sedimenting into the upper troposphere may alter cirrus cloud microphysics, thus producing a possibly significant climate forcing, which is uncertain even as to sign.

Unfortunately, no global data exist that are adequate to define any of these aerosol climate forcings.

Aerosols can be seen against the dark ocean surface by the imaging instruments on present operational meteorological satellites (Rao *et al.*, 1988; Jankowiak and Tanre, 1992). For example, these images clearly show Sahara/Sahelian dust spreading westward from Africa, summertime sulfate aerosols moving eastward from the United States, and aerosols from seasonal biomass burning in the tropics. However, the nature and accuracy of these data are inadequate to define the climate forcing, and, indeed, the observed optical depths may be in part thin cirrus clouds. The climate forcing issue requires aerosol data of much higher precision, including information on aerosol altitude and aerosol physical properties such as size and refractive index. Cloud properties, including optical depth, particle size, and phase, must be monitored simultaneously to very high precision, so that the temporal and spatial variations of aerosols and clouds can be used to help define the indirect aerosol climate forcing.

Stratospheric aerosol optical depth was monitored in the polar regions from late 1978 until 1994 by a solar occultation instrument (SAGE I) on the Nimbus-7 spacecraft (McCormick *et al.*, 1979). The record reveals seasonal polar stratospheric (condensation) clouds, especially in Antarctica, as well as the influence of aperiodic volcanic sulfuric acid aerosols, especially the El Chichon eruption in 1982 and the Mt. Hudson and Mt. Pinatubo eruptions in 1991. An approximate 50% increase of 'background' aerosol optical depth between 1979 and 1990 is thought by some (e.g., Hofmann, 1990) to be a result of anthropogenic impact on the sulfur cycle, perhaps due to aircraft emissions.

The global radiative forcing of the El Chichon aerosols reached a maximum of about –2 W/m^2 (Hansen and Lacis, 1990) and the forcing by Pinatubo aerosols was even larger (Hansen *et al.*, 1992, 1993a; Minnis *et al.*, 1993), thus exceeding the magnitude of the forcing by all anthropogenic greenhouse gases, though opposite in sign. Although the aerosol forcing from individual volcanic eruptions is more short-lived, it must be monitored if the global temperature record is to be interpreted. The Nimbus-7 spacecraft measuring polar stratospheric aerosols ceased operations recently. SAGE II has been obtaining data at low and middle latitudes from the ERB spacecraft since 1984, but that spacecraft is showing signs of age and is already well beyond its design life.

Solar irradiance. Another potentially important climate forcing is change of solar irradiance. The spectrally integrated irradiance has been monitored for about 15 years, showing a decline of about 0.1% between 1979 and 1986, followed by at least a partial recovery. If this measured variability were spectrally uniform, it would imply a climate forcing of about 0.3 W/m^2 of absorbed solar energy. Solar variability of a few tenths of a percent could cause a global temperature change of the magnitude of the observed cooling between 1940 and 1970, and there have been suggestions that the sun may be responsible for the warming trend of the past century (Friis-Christensen and Lassen, 1991). Thus we need to monitor solar irradiance on longer time scales, including the spectral distribution of changes, because the nature of the solar forcing varies strongly depending on the altitude where the radiation is absorbed. There are offsets of the absolute irradiance even among the best calibrated instruments (Lean, 1991), which implies the necessity of overlapping coverage by successive instruments for successful monitoring.

Surface reflectivity. Perhaps the next climate forcing mechanism to be rediscovered as a competitor to increasing greenhouse gases is change of the Earth's surface reflectivity. Sagan *et al.* (1979) argued that anthropogenic deforestation and desertification could have increased the planetary albedo sufficiently to cause a cooling of about 1 °C over the past few millennia, and may have been responsible for the observed global cooling after 1940. Potter *et al.* (1981) calculated a smaller global cooling, 0.2 °C, with a two-dimensional climate model, but nevertheless surface albedo change is a potentially significant climate forcing. For example, a change of mean land albedo from 0.15 to 0.16 would cause a global climate forcing of about 0.5 W/m^2, comparable in magnitude to the forcing due to expected increases of anthropogenic greenhouse gases during the next two decades. Although a global mean change that large may be unlikely, regional effects could be substantial and the global effects need to be quantified.

Operational meteorological satellites currently measure the Earth's surface reflectivity at one or two wavelengths, but the instruments are not calibrated well enough to provide reliable long-term data (Brest and Rossow, 1992). However, it is not difficult to obtain both higher accuracy and precision than that of the meteorological instruments, which were not designed for long-term climate monitoring. More complete spectral coverage also is needed because vegetated regions in particular have a strong, seasonally variable, spectral dependence of reflected radiation.

Radiative feedbacks. There are many feedback processes, some known and others yet to be discovered, which alter the climate system's ultimate response to a climate forcing. In studies with current GCMs, it has been found that the net response of global temperature to a forcing such as doubled carbon dioxide can be separated quantitatively into contributions arising from the forcing plus three major radiative feedbacks: (1) changes of atmospheric water vapor, and its vertical distribution; (2) changes of cloud cover, optical depth, and altitude; and (3) changes of the duration and area of ice and snow cover (Cess *et al.*, 1989, 1990, 1991; Schlesinger and Mitchell, 1987; Hansen *et al.*, 1984). For example, for doubled CO_2 the no-feedback climate sensitivity of 1.2–1.3 °C is increased to about 2–5 °C in the GCM simulations, with the latter value depending upon the strength of these three feedbacks in each global model.

As indicated by the schematic Figure 3, the largest feedback in the GCMS is caused by water vapor. Lindzen (1990) maintains that the models exaggerate the water vapor feedback and has argued that the feedback could be negative. Although there is theoretical and empirical evidence against Lindzen's hypothesis of a negative feedback (Betts, 1991; DelGenio *et al.*, 1991; Rind *et al.*, 1991; Raval

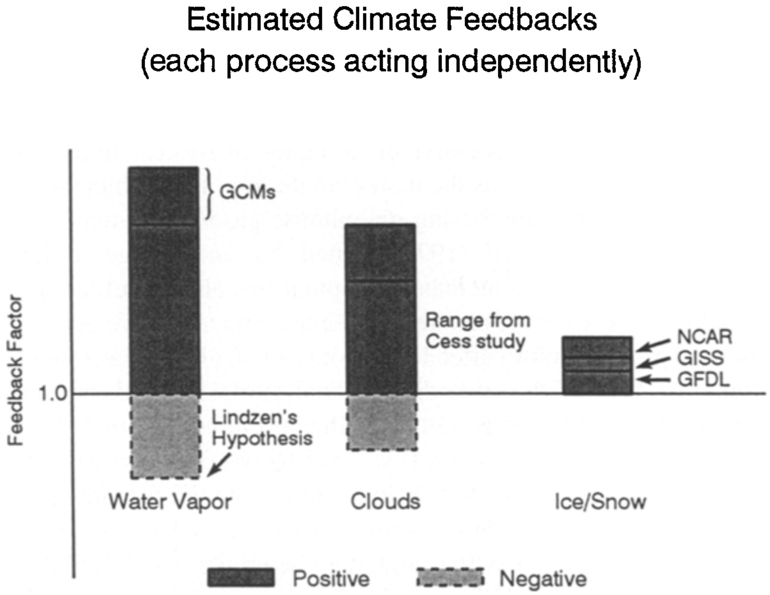

Fig. 3. Schematic indication of the radiatiative feedback factors which have been found to determine the global sensitivity of the general circulation models to climate forcings such as doubled atmospheric CO_2 (Hansen *et al.*, 1993b).

and Ramanathan, 1989), this does not diminish the importance of changes of the water vapor profile in determining the magnitude of the water vapor feedback. Cloud feedbacks are probably the most uncertain, with the range from GCMs including negative as well as positive feedbacks (Cess *et al.*, 1989, 1990). The ice/snow feedback also shows a wide variation among models (Cess *et al.*, 1991; Randall *et al.*, 1994).

Climate feedbacks are the cause of large uncertainty about climate sensitivity to a specified forcing. Continued efforts to improve the representation of the feedback processes in climate models are important and are receiving much attention, but it is unlikely that general agreement on the magnitude of global feedbacks on longer time scales can be obtained on the basis of only process studies and models. Thus it is crucial that observations of current and future climate change be accompanied by measurements of the feedbacks to an accuracy sufficient to define their contribution to observed climate change. As we demonstrate below, it is possible to obtain the required accuracies with existing technology.

It is appropriate to ask whether there are other important climate forcings or feedbacks, in addition to those wich the scientific community has already identified. Although the processes that have been considered account for all the major mechanisms for exchange of energy with space, it is likely that there will be future surprises in our understanding of both climate forcings and feedbacks. Therefore, it is important that a monitoring strategy include measurements covering practically the entire spectra of both the solar and thermal radiation emerging from the Earth, because all radiative forcings and feedbacks operate by altering these spectra. Although efforts to measure integrated reflected solar and emitted thermal fluxes are underway (Kandel, 1990), measurement of changes in the spectral distribution of the radiation are required to provide diagnostic information about causes of flux changes.

Monitoring Rationale

Ambiguity would persist in interpretation of observed temperature changes even if all global climate forcings and feedbacks were measured accurately, because of possible but unmeasured changes of atmospheric and oceanic energy transports. Nevertheless, a long-term record of the forcings and feedbacks will provide a very strong constraint on interpretation of future global temperature change.

Our rationale is inspired by Keeling's CO_2 record, which is a prototype of high-precision long-term monitoring of a climate parameter. The CO_2 record cannot by itself provide an understanding of either the global carbon cycle or the global thermal energy cycle, but it provides a very strong constraint. Also, the CO_2 monitoring is not competitive with detailed observations required to understand carbon and thermal energy processes. On the contrary, it inspires and helps guide such studies. Note that CO_2 monitoring, after being proven as a research product, became an operational activity of NOAA. Similarly, monitoring of other climate forcings and feedbacks could become an operational activity once a measurement approach is demonstrated.

Many of the missing climate parameters can be measured by three small instruments which we describe below. These instruments measure with high precision the spectra of reflected solar radiation and emitted thermal radiation. We have used observed global datasets and global climate models to determine the minimum measurements needed to define changes of the climate forcings and feedbacks with the required accuracies on seasonal and longer time scales, as described in the Climsat report (Hansen *et al.*, 1993b). A more detailed consideration of cloud monitoring is presented by Rossow and Cairns (1995). The fewest number of satellites required is two. A sun-synchronous near-polar orbiter provides a fixed diurnal reference. A precessing orbiter inclined 50–60 degrees to the equator provides a statistical sample of diurnal variations at latitudes with significant diurnal change. The need to determine diurnal changes has been highlighted by the discovery that global warming of the past several decades has a strong day/night asymmetry (Karl *et al.*, 1993). The two orbits together provide good global observing conditions for all three instruments and reduce sampling errors below the level required for detecting expected decadal time-scale change. Two satellites are also required to allow satellite-to-satellite transfer of calibration when one satellite fails and must be replaced.

Climsat is low-cost. The Climsat instruments have well-proven long-lived predecessors; thus their production can take advantage of, but does not depend upon, costly technological advances. They are light-weight (about 25 kg without SAGE, or 60 kg with SAGE), permitting launch by a Pegasus-class vehicle. These characteristics make Climsat economically feasible for repeated missions over decades.

The three instruments we propose would provide many of the missing climate forcings and feedbacks, but certain complementary monitoring is required to complete the full set of data requirements. One particular need is long-term satellite monitoring of both the total and spectral solar irradiance; this data is presently being obtained by the UARS mission, but there is urgent need of real plans for continued monitoring, which could be effectively carried out by a small satellite. Also satellite monitoring of parameters such as tropospheric aerosols and the ozone profile must be supplemented by ground-based monitoring networks to assure acquisition of complete climate forcing and feedback information. This is discussed further below.

Proposed Climsat Measurements

Measurements by the three proposed Climsat instruments cover practically the entire thermal and solar spectra, as summarized in Figure 4, and are designed to exploit the information on gases, aerosols and clouds contained in these spectra. In the thermal wavelength region information is contained primarily in the high resolution spectral variations of the radiance (Conrath *et al.*, 1970; Hanel *et al.*, 1972; Kunde *et al.*, 1974; Clough *et al.*, 1989). On the other hand, because incident sunlight is unidirectional, reflected solar radiation is in general strongly polarized, and the polarization is highly diagnostic of aerosol and cloud properties (Hansen and Travis, 1974; Coffeen and Hansen, 1974). The full spectral coverage of the Climsat instruments is a crucial characteristic of the proposed measurements, because it means they should be capable of providing information on climate 'surprises', as well as the climate forcings and feedbacks about which we already know, because all radiative forcings and feedbacks operate by altering the solar or thermal spectrum in some way.

SAGE III (Stratospheric Aerosol and Gas Experiment III) observes the sun and moon through the Earth's atmosphere, obtaining extinction profiles with very high vertical resolution. SAGE III uses the same grating spectrometer as its immediate predecessors, but, unlike them, it records the spectrum on a continuous linear array of detectors, yielding a spectral resolution of 10 Å (10^{-3} μm) from 0.29 μm to 1.02 μm. It also adds a detector at 1.55 μm to improve determination of aerosol sizes and provide discrimination between aerosols and thin cirrus clouds. SAGE III will provide absolutely calibrated profiles of stratospheric aerosols, stratospheric water

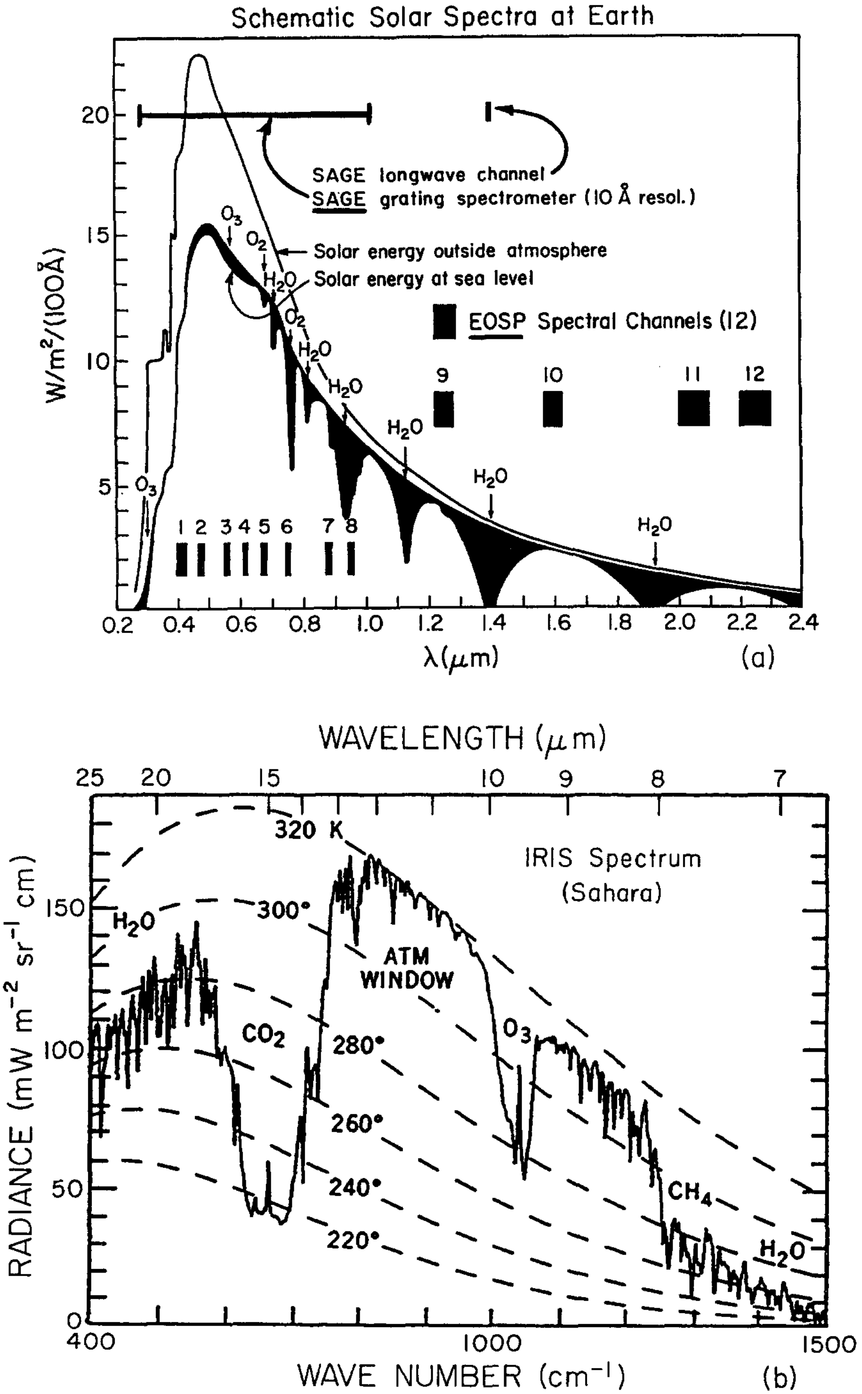

Fig. 4. Approximate spectral regions covered by proposed instruments: (a) Location of the EOSP and SAGE III spectral channels, relative to a typical spectrum of solar radiation; (b) Example of terrestrial thermal spectrum, obtained by the Nimbus-3 IRIS instrument over the Sahara desert. MINT will have a somewhat broader spectral coverage, 250–1700 cm^{-1}, and higher resolution (2 cm^{-1}).

vapor, and ozone, extending and improving upon predecessor data (McCormick, 1993).

MINT (Michelson Interferometer) covers the spectral range 5–50 μm, the longer wavelengths being important for defining the water vapor distribution. Its high spectral resolution and high wavelength-to-wavelength precision provide the essential ingredients for accurate long-term monitoring of cloud properties (cloud cover, effective temperature, optical thickness, ice/water phase and effective particle size) day and night in six 8 km fields of view. MINT simultaneously monitors tropospheric water vapor, ozone and temperature (Lacis and Carlson, 1993).

EOSP (Earth Observing Scanning Polarimeter) covers the solar spectrum from the near ultraviolet (0.4 μm) to the near infrared (2.25 μm) in 12 spectral bands, obtaining global maps of the radiance and polarization with a spatial resolution of 8 km at the subsatellite point. Its unique contributions are accurate global distribution and physical properties of tropospheric aerosols (optical thickness, particle size and refractive index) and precisely calibrated surface reflectance. In addition, EOSP yields detailed cloud properties, complementing and refining cloud information from MINT (Travis, 1993).

Table I summarizes specific technical data on each of the three instruments. A more detailed description of the instruments is given in the workshop report (Hansen *et al.*, 1993b) and references provided there.

Perhaps the most crucial characteristic of the Climsat instruments is that they are all self-calibrating to high precision. The SAGE calibration is obtained by viewing the sun (or moon) just before or after every occultation. MINT records its interferogram on a single detector, thus obtaining high wavelength-to-wavelength precision. Absolute calibration of the MINT measurements is achieved by periodic viewing of space (cold reference) and an internal black body (warm reference). EOSP interchanges the roles of its detector pairs periodically by using a stepping half-wave retarder plate, calibrating polarization to 0.2% absolute accuracy. The EOSP radiance calibration is based primarily on internal lamps with a demonstrated stability of better than 2% per decade, implying a decadal precision for surface reflectivity of better than 0.002 for a surface reflectivity of 0.1. This radiance calibration stability exceeds that of operational satellites by a factor of about five (Brest and Rossow, 1992).

All three Climsat instruments are based on space-proven predecessors, with incremental but significant enhancements in capability, incorporating recent advances in detector and electronic technology. Each of the three instruments has a predecessor with a lifetime in space exceeding 10 years.

The original Climsat concept had these three instruments together on a small satellite. Recently funding has been approved for three SAGE III instruments, with the first two flights expected to be on a Russian polar orbiting satellite and the inclined orbiting space station. Thus one strategy for completing the proposed set of Climsat measurements would be to fly the MINT and EOSP instruments on a smaller spacecraft. These two instruments need to be on the same spacecraft, with

TABLE I

Climsat sensors

SAGE III	EOSP	MINT
Earth-limb scanning grating spectrometer, UV to near IR, 10 Anstrom resolution.	Along-track scans of radiance and polarization, 12 bands near UV to near IR.	Michelson interferometer, 2 cm^{-1} resolution from 5 μm to 50 μm; nadir viewing by 2×3 array of detectors.
IFOV = 30 arcsec (~0.5 km); inversion resolution 1–2 km.	IFOV = 12 mrad (8 km at nadir).	IFOV = 12 mrad (8 km from 650 km altitude).
Yields profiles of T, aerosols, O_3, H_2O, NO_2, NO_3, OClO – most down to cloud tops.	Yields aerosol optical depths, particle size and refractive index, cloud optical depth and particle size, and surface reflectance and polarization.	Yields cloud temperature, optical depth, particle size and phase, temperature, water vapor and ozone profiles and surface emissivity.
Mass: 35 kg	Mass: 16 kg	Mass: 10 kg
Power (mean/peak) 10/45 W	Power (mean/peak): 15/22 W	Power (mean/peak): 14/22 W
Mean Data Rate: 0.45 Tbpy*	Mean Data Rate: 0.8 Tbpy*	Mean Data Rate: 0.7 Tbpy*
Cost: About $20M for first copy, about $10M each additional copy	Cost: About $20M for first copy, about $10M each additional copy	Cost: About $20M for first copy, about $10M each additional copy

* Tbpy = Terabits/year, Mission comparison: ISCCP = 0.2 Tbpy; CLIMSAT = 4 Tbpy; EOS = 2500 Tbpy [one Terabit is approximately 1000 tapes (6250 bpi) per year].

their identical fields of view boresighted at nadir, so that the information obtained on clouds, atmosphere and surface is enhanced.

Estimated Measurement Accuracies

Specification of measurement accuracy requirements and instrument capabilities is difficult and somewhat subjective. Nevertheless, it is important to provide plausible estimates of needs and capabilities. As summarized below, we considered two independent criteria for specifying accuracy requirements (Chapters 3 and 7 in Hansen *et al.*, 1993b). The estimates of instrument capabilities were based on consideration of predecessor instrument performance, planned instrument improvements, and Climsat sampling characteristics. Actual capabilities can only be determined after the fact, but we note that it is not unusual for ultimate capabilities to exceed expectations in the case of stable calibrated instruments.

The first criterion for accuracies was based on the desire to simply detect plausible changes of the forcings and feedbacks estimated to be possible during the next 20 years, as discussed by DelGenio (1993). The second criterion was the more demanding desire to determine quantitatively the contribution of every significant forcing and feedback to the planetary energy balance. We defined a significant global mean flux change as 0.25 W/m^2 or greater, based on the consideration that anticipated increases of greenhouse gases during the next 20 years will cause a forcing of about 1 W/m^2. The accuracy requirements resulting from these two criteria are listed in Table II. Although the precise magnitudes are uncertain, the indicated values are plausible and consistent with current understanding of the climate system.

The capabilities of the proposed Climsat mission depend on the instrumental accuracies and precisions, and also on the spatial and temporal sampling from the Climsat orbits. The instrumental capabilities are discussed in Sections 8–10 and the sampling in Sections 11–12 of the Climsat workshop report (Hansen *et al.*, 1993b). Predecessor SAGE instruments provide the basis for expected accuracies of the improved SAGE III. Estimates of retrieval precisions for MINT are based mainly on analysis of data from the Infrared Interferometer Spectrometer (IRIS) instrument, accounting for expected decreases in instrument noise levels. EOSP has an inherent advantage over instruments measuring only reflected radiance, because its high accuracy measurement of linear polarization is very sensitive to particle microphysics (Hansen and Travis, 1974). The nonuniqueness in retrievals based on the radiance can be overcome using the polarization, as demonstrated by Pioneer Venus retrieval of the properties of haze particles located above and within a lower cloud deck (Kawabata *et al.*, 1980). Comparable complications exist for aerosols over land-vegetation surfaces on Earth, but present evidence that the polarization from vegetated surfaces derives mainly from specular reflection at leaf surfaces (Vanderbilt *et al.*, 1985), together with the broad EOSP wavelength coverage, suggests that the surface contributions can be accurately accounted for in the EOSP retrievals.

Reliable determination of the ultimate retrieval capabilities prior to flight of the instruments is extremely difficult, but further simulations of instrument performance, data inversion techniques, and sampling studies are being pursued. Sampling studies for the stratospheric quantities, for example, are hindered by inadequate knowledge of small scale spatial variability of the parameters being measured. Our present estimates of potential Climsat capabilities are given in the fourth column of Table II for regional (1000 km by 1000 km), seasonal (3 month) averages and in the fifth column for global decadal change. Generally the sampling is not a factor in determining the global decadal change, but it does influence the ability to determine regional seasonal change.

It appears that, in general, these instruments are capable of measuring the changes of climate forcings and feedbacks projected as being plausible during the next 20 years. The more difficult criterion, quantifying the flux changes to 0.25 W/m^2, can also be achieved for all the climate forcings except aerosol induced cloud changes. But this latter forcing may be measurable in the regions of largest (measured) aerosol changes, which may allow an inference of the corresponding

TABLE II

Comparison of estimated Climsat measurement accuracies with changes of forcing and feedback parameters anticipated on a 20 year time span (A. DelGenio, Chapter 3 in Hansen *et al.*, 1993b) and with the parameter changes required to yield a flux change of 0.25 W/m^2

Forcing or feedback	Plausible 20 year change	Global change required to yield $\Delta Flux = 0.25$ W/m^2	Climsat accuracy estimated for regional seasonal mean	Climsat accuracy estimated for global decadal change
Ozone	Altitude and height dependent	10% of O_3 at 15–20 km	10%	3%
Stratospheric H_2O	$\frac{\Delta q}{q} = 0.3$	0.25	0.10	0.03
Stratospheric aerosol	$\Delta\tau = 0.04$	0.01	0.02	0.002
Tropospheric aerosol	$\Delta\tau = 0.04$	0.01	0.02	0.005
Total solar irradiance	0.1–0.3%	0.1%	not on Climsat, but ACRIM, if flown *continuously*, could readily achieve the needed accuracy	
Surface (land) reflectivity	0.01 (land)	0.006 (land)	0.01	0.003
Tropospheric H_2O				
upper	$\frac{\Delta q}{q} =$ 0.1	0.02	0.05	0.03
lower	0.04	0.02	0.03	0.02
Cloud cover				
cirrus	$\Delta C =$ 0.03 (regional)	0.004	0.02	0.004
stratus	0.03 (regional)	0.003	0.02	0.004
Cloud top				
temperature	$\Delta T = 1$ K	0.4 K	1 K	0.3 K
pressure	$\Delta p = 12$ mb	5 mb	15 mb	5 mb
Cloud optical depth				
cirrus	$\Delta\tau =$ 0.1	0.02	0.1	0.05
stratus	1	0.07	0.5	0.2
Cloud particle size (water)	$\Delta r = 1\ \mu$m	0.2 μm	0.5 μm	0.2 μm

global forcing. It appears that these instruments may be just marginally capable of measuring most of the feedbacks, mainly cloud parameter changes, to the 0.25 W/m^2 criterion. Direct measurement of cloud optical thickness change to this accuracy does not seem to be achievable. The alternative of measuring the corresponding cloud albedo changes over decades is also estimated to be just outside the capability which is proven for the EOSP calibration lamps on the basis of planetary flight experience. However, we emphasize that the accuracies considered here are several times better than those of current meteorological satellites, which are already capable of detecting some interannual changes (Ardanuy *et al.*, 1992).

In summary, these instruments are capable of detecting plausible decadal changes of many climate forcings and feedbacks. In most cases, the forcings and feedbacks can be quantified to the high precision (0.25 W/m^2) desired to help interpret global climate change. The merits of precise long-term monitoring of the fundamental climate data represented by the solar and thermal spectra also can be argued simply on the basis of analogous examples such as Keeling's CO_2 monitoring. However, the fact that it appears feasible to derive climate parameters with an accuracy at least approaching that needed to interpret flux changes of 0.25 W/m^2 makes the case even stronger.

Complementary Monitoring Requirements

Although the proposed instruments can provide with the required accuracies many of the climate forcings and feedbacks missing from the existing observational system, other monitoring is needed to complete the full set of data requirements. We summarize the key requirements here.

Perhaps the most crucial need is long-term monitoring of the sun, which provides the ultimate drive for the Earth's climate. A plausible case has been made that solar irradiance changes might be responsible for climate changes such as those characterized by the Little Ice Age (Eddy, 1976), which may only require solar changes of several tenths of a percent (Wigley, 1988; Wigley and Kelly, 1990). Precise monitoring of the total solar irradiance during the past decade (Willson and Hudson, 1991; Hoyt *et al.*, 1992) confirmed the existence of significant variations of solar irradiance, of the order of 0.1% over the last 11 year solar cycle. It is important that this fundamental measurement be continued. There must be an overlap of the successive monitoring instruments, because it is not possible to obtain sufficient absolute accuracy of the irradiance (Lean, 1991). The UARS mission (Reber, 1990) includes ACRIM II, which precisely monitors total solar irradiance, but prompt flight of another ACRIM or its equivalent is needed.

It is also important to monitor the spectrum of the solar irradiance. The climate forcing due to solar change is entirely different if the change occurs at wavelengths absorbed in the upper atmosphere, as opposed to wavelengths which reach the troposphere. Furthermore changes in ultraviolet irradiance may cause an indirect climate forcing by altering the abundances of greenhouse gases such as ozone (Chandra, 1991; Stolarski *et al.*, 1991). The UARS mission includes two instruments which monitor the solar spectral irradiance in the ultraviolet region, where large variability is known to occur (Rottman, 1988), but plans for a follow-up are needed. Total and spectral irradiance monitors both appear to be prime candidates for flight on small satellites.

Several of the parameters which our proposed instruments can monitor require complementary detailed measurements from ground stations, specifically ozone, tropospheric aerosols and tropospheric water vapor. The change of the ozone profile in the upper troposphere and lower stratosphere is difficult to measure accurately from space, because that region lies below the bulk of the ozone. A crude measure of total tropospheric ozone change can be obtained by combining SAGE and TOMS satellite data (Fishman *et al.*, 1990), but this does not provide an accurate measure of ozone climate forcing. Although the increased sensitivity of the SAGE III instrument should increase the accuracy of the ozone profile in the tropopause region, it is also important to have monitoring from a number of well placed ground stations. If the plans for the Network for Detection of Stratospheric Change (Kurylo and Solomon, 1990) and plans for tropospheric monitoring (Prinn, 1988) are implemented, and if SAGE III flies in both polar and inclined orbits, monitoring of the ozone profile will probably be adequate for the purpose of defining ozone climate forcing.

Similarly, monitoring of tropospheric aerosols from space with the required high precision is difficult and the capabilities remain to be proven. It will be important to have detailed aerosol monitoring at a number of continental and marine stations and periods of special detailed study to verify changes detected from satellites and obtain additional aerosol properties. Regional ground-based aerosol monitoring networks need to be supported and strengthened. In the United States the Department of Energy ARM sites are expected to make aerosol measurements which are hopefully the beginning of long-term monitoring. As inexpensive sunphotometers are capable of accurate local aerosol measurements, it may be feasible to involve schools in maintaining instrument sites and working with the data, thus yielding useful climate data while providing valuable science educational experience.

Several satellite instruments can measure upper tropospheric water vapor, a key climate feedback parameter influencing climate sensitivity. But such measurements need to be supplemented by a reference network of radiosondes with improved calibration aided by use of a traveling calibration standard.

Relation to Climate Process and Diagnostic Studies

Long-term monitoring of global climate forcings and radiative feedbacks is, of course, only a portion of required global climate measurements (cf., USGCRP, 1993). There is also need for monitoring of climate diagnostics and for detailed measurement and analysis of a number of climate processes, especially relating to the oceans, clouds, precipitation, and fluxes between the surface and the atmosphere. It is important that measurements of these climate diagnostics and processes proceed apace with the long-term climate monitoring of climate forcings and radiative feedbacks. The combination of improved knowledge of changing climate forcings and radiative feedbacks, together with improved understanding and modeling of climate processes, is required to obtain predictive capability for future climate.

The rate at which the climate system responds to a change of climate forcing depends upon how rapidly a heat perturbation mixes into the ocean, which requires appropriate knowledge of ocean circulation. Moreover, it is essential to understand how ocean circulation may change in response to atmospheric changes (Broecker, 1987). The WOCE (World Ocean Circulation Experiment) program (WCRP, 1986), especially if it is continued and expanded, promises to improve our understanding of ocean circulation and its relation to atmospheric climate change. Acoustic tomography, in particular the proposed near-global expansion of the Heard Island experiment (Munk and Forbes, 1989), appears to have exciting potential for monitoring heat uptake by the ocean on decadal time scales. This needs to be complemented by a continuing series of altimetry and scatterometer space missions, together with a reference network of moored buoys, to measure surface winds and ocean currents.

Clouds are probably the most uncertain climate feedback. In addition to monitoring of possibly small decadal cloud changes, it is important to make detailed observations which allow us to understand and model cloud processes better. The EOS mission, which includes the CERES instrument and relatively high resolution imaging, should provide an improved ability to analyze the relation of clouds and the earth's radiation budget, as well as other cloud studies, because almost all of the EOS instruments have some cloud measurement objectives.

Precipitation is a climate diagnostic of great practical importance. Moreover, changes of precipitation can complicate attempts to interpret long-term temperature changes, because of the latent heat associated with evaporation and precipitation. Although there is no expectation that rain rates will be monitored with a precision comparable to that attainable for the radiative forcings and feedbacks, it is important that rainfall monitoring be advanced as much as practical, to improve the simulation and prediction capability of climate models. Thus the TRMM mission (Simpson *et al.*, 1988) planned for 1997 should be just the beginning of a rainfall monitoring satellite series, with measurement capabilities and coverage that improve with time.

Fluxes between the atmosphere and the earth's surface of energy, momentum, water, carbon, and other substances are intimately involved in the functioning of the earth's climate. Many measurements related to these fluxes will be obtained by EOS, and these data should contribute toward improved modeling of climate processes. Many of these data would be more valuable if they were accompanied by accurate measurements of near surface winds; this requires advances in instrument technology and may be a good candidate for a focused small satellite mission. Regional ground-based and ocean field studies are also essential for improved understanding of surface fluxes.

We emphasize that the EOS and other planned experimental measurements are complementary to the monitoring of the proposed Climsat instruments, but the existence of these projects does not negate the need for the proposed Climsat monitoring. For example, EOS does not measure all climate forcings and is not well suited for long-term monitoring. Because of its high cost and the absence of 'hot spares' to replace a failed instrument or spacecraft, EOS is not likely to provide continuous multidecadal monitoring. EOS does not provide the required space-time sampling and coverage as Climsat, which proposes two identical satellites, one with a precessing inclined orbit. The Climsat approach also allows instrument cross-calibration when one must be replaced, which is critical to long-term data precision. EOS does not adequately sample diurnal variations, which are particularly important in defining cloud forcings and feedbacks. EOS does not plan to address the greatest uncertainty in human-made climate forcings, lower atmospheric fine particles, with the required precision until the second AM spacecraft in 2004. The very high wavelength-to-wavelength precision of the Michelson Interferometer proposed for Climsat, which uses a single, passively cooled detector without scanning, is crucial for obtaining the required accuracy. In contrast, the infrared spectrometer on EOS uses separate detectors for each eavelength, requiring individual calibrations, is actively cooled and does not cover the thermal spectrum either continuously or as extensively as MINT.

Discussion

The concept of monitoring missing climate forcings and feedbacks with small inexpensive satellites was discussed by one of us (JEH) in December 1989 at a round-table meeting chaired by Senator Albert Gore, in response to Senator Gore's request for suggestions to reduce uncertainties about global change. Senator Gore asked for a written description of the small satellite proposal, which led to a publication in Issues in Science and Technology (Hansen *et al.*, 1990). On the basis of that article, Congress allocated funds in 1991 to initiate Climsat, but the funding was rescinded by Congress when the program was not initiated. Subsequently, formal proposal of this small satellite concept has awaited the possibility of open competition via an Earth Probe budget line. Such a small satellite budget line has been discussed in connection with recent NASA budgets, but it has not received a priority sufficient to obtain funding.

Independently of Climsat, funding has been approved to build three copies of the SAGE III instrument with the first two expected to be placed on already planned polar and inclined orbit missions. As the limb-viewing SAGE III does not view the same region simultaneously with the downward-looking instruments, there is no scientific requirement that it be on the same spacecraft as the other Climsat instruments. MINT and EOSP, on the other hand, have identical fields-of-view at nadir and need to be on the same satellite to enhance information on cloud, atmospheric and surface properties. In view of the new plans for SAGE, this suggests the possibility of including MINT and EOSP, whose combined mass is less than 40 kg, on an even smaller spacecraft. Such a satellite could also be used for later follow-on flights of SAGE III as a single instrument, since the SAGE III mass is about 40 kg. These alternatives should be explored if a small satellite budget line with open competition becomes a reality.

A satellite-borne lidar could provide valuable data on tropospheric aerosols and clouds, complementary to that of EOSP and MINT. A lidar measures backscattering, which is not simply related to optical depth, but it provides precise determination of vertical layering. It would be particularly useful to have lidar measurements nearly simultaneous with those of Climsat. A lidar on a small satellite launched to fly ‘in formation’ with Climsat would provide an important test of this approach for Earth monitoring.

Perhaps the most difficult challenge for long-term monitoring of climate forcings and feedbacks is the tropospheric fine particles (aerosols) and associated cloud changes. Although the proposed Climsat instrument EOSP has better capabilities for measuring aerosols than existing instruments, it would need to be coordinated with ground based measurements at a number of globally distributed sites. We believe it would be possible for schools, supported by scientists in their regions, provided with training, and connected by computer network to a coordinating center, to make valuable contributions to this climate monitoring. Specifically, a multichannel sunphotometer can be used to measure aerosol amount (optical depth and size), as well as other relevant quantities such as ozone, water vapor and cloud cover. In conjunction with appropriate curricula, these measurements of the solar spectra could provide valuable science learning experience. It is notable that the concept of involving school students in significant scientific measurements was introduced by Senator Gore at the same 1989 round-table discussion mentioned above.

We note that the Climsat data and data products would be well suited to contribute to teaching Earth sciences in schools because the Climsat data would provide a low volume, comprehensive, on-going description of important climate parameters. Global maps of monthly-averaged distributions of surface and atmospheric properties, routinely distributed over Internet, will reveal seasonal and interannual changes which can be used to illustrate global change topics to students. The measurements of both solar and thermal spectra are fundamental quantities which can be related to curricula topics. Curricula could be designed not only to give the typical student some understanding of global change and a taste of how scientific research is performed, but to challenge the precocious ones to get involved in actual global change research.

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Acronyms

ACRIM:	Active Cavity Radiometer Irradiance Monitor
ARM:	Atmospheric Radiation Measurements (DOE program)
AVHRR:	Advanced Very High Resolution Radiometer (flown on NOAA satellites)
CFCs:	Chlorofluorocarbons
CERES:	Clouds and the Earth's Radiant Energy System (EOS instrument)
DOE:	U.S. Department of Energy
EOS:	Earth Observing System
EOSP:	Earth Observing Scanning Polarimeter (EOS instrument)
ERBS:	Earth Radiation Budget Satellite
GCM:	Global Climate Model or General Circulation Model
GISS:	Goddard Institute for Space Studies (NASA)
GLOBE:	Global Learning and Observations to Benefit the Environment
IPCC:	Intergovernmental Panel on Climate Change
ISCCP:	International Satellite Cloud Climatology Project
MINT:	Michelson Interferometer
NASA:	U.S. National Aeronautics and Space Administration
NOAA:	U.S. National Oceanic and Atmospheric Administration
SAGE:	Stratospheric Aerosol and Gas Experiment (EOS instrument)
TOMS:	Total Ozone Mapping Spectrometer
TRMM:	Tropical Rainfall Measuring Mission (Japan-U.S. satellite mission)
UARS:	Upper Atmospheric Research Satellite
USGCRP:	United States Global Change Program
WCRP:	World Climate Research Program
WMO:	World Meteorological Organization
WOCE:	World Ocean Circulation Experiment

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