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# **Long-Term Monitoring of Global Climate Forcings and Feedbacks**

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# Long-Term Monitoring of Global Climate Forcings and Feedbacks

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## PREFACE

A workshop, Long-Term Monitoring of Global Climate Forcings and Feedbacks, was held February 3-4, 1992, at the NASA Goddard Institute for Space Studies. The purpose was to discuss the measurements required to interpret long-term global temperature changes, to critique the potential contributions of a proposed series of small satellites (Climsat), and to identify complementary monitoring which would also be required.

Subsequent to the workshop, the Climsat proposal was presented at the Committee on Earth and Environmental Sciences workshop on small satellites, held February 12-14, and at the Congressional Office of Technology Assessment workshop on the future of remote sensing technology, held April 21. On the advice of NASA management, review of the Climsat proposal by the NASA Earth Science and Applications Advisory Committee was requested, but is not yet scheduled.

A first draft of this workshop report was produced from written contributions of the speakers whose papers were central to the rationale and definition of the Climsat proposal, as well as from summaries of each session and the panel discussion prepared by the respective chairmen. We note that the workshop conclusions were not specifically set down and agreed upon at the workshop, but rather were drafted by the editors from the consensus of workshop discussions and then refined based on review by all participants. The resulting draft report was widely circulated among the climate research community.

This final version of the workshop report is intended to provide the rationale and strategy for a specific small satellite flight and research program. However, several respondents pointed out that the report may also be viewed as a broader planning document, and they suggested that we emphasize up front the relationship between the proposed Climsat program and other important climate measurements. Thus in the executive summary we briefly place the proposed Climsat program in broader context.

We would like to acknowledge major contributions to the preparation of this report from Christina Koizumi, who served as technical editor, Brian Cairns, Ken Lo and Alison Walker, who contributed to the orbit and sampling section, and Michael Mishchenko, who contributed to the scanning polarimeter section.

We also gratefully acknowledge written responses to earlier drafts of this report from a large number of scientists in addition to those who attended the workshop, including at least: B. Albrecht, T. Anderson, R. Bradley, T. Busalacchi, M. Cane, P. Chylek, J. Coakley, E. Dutton, J. Fein, C. Folland, E. Frieman, H. Grassl, J. Gribben, J. Hovenier, D. Hoyt, R. Jenne, J. Jouzel, Y. Kawata, J. Kiehl, K. Kondratyev, G. Kukla, T. Malone, L. Meredith, W. Munk, T. Nakajima, H. Oeschger, D. Randall, A. Robock, E. Rodenburg, C. Sagan, M. Salby, U. Siegenthaler, J. Simpson, C. Sonett, A. Thompson, R. White, R. Willson, and C. Wunsch. Although the overall response to the draft reports was highly favorable, we do not mean to imply that all these scientists necessarily endorse the workshop conclusions.

## EXECUTIVE SUMMARY

Climate varies on all time scales, and there are many aspects of climate change with practical importance. Without prejudice to other issues, our workshop focused 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 called attention to the need for high precision monitoring of all major global climate forcings, as an essential requirement for interpretation of global climate 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 such policy decisions are made, continued monitoring of the climate forcings to a precision that accurately defines their changes will be necessary in order to judge the effectiveness of the policies.

In this report we identify the principal global climate forcings and radiative feedbacks. Climate forcings are 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. 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 certain other climate forcings and radiative feedbacks not included on Climsat, as well as the need for complementary field projects and measurements from a small number of "ground truth" surface stations. Together with existing observations, these measurements will strongly constrain interpretation of observed global temperature change and permit quantitative comparison of climate forcing mechanisms which presently involve substantial uncertainty.

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 not meant to be the sole source of measurements of long-term climate change, but rather would be a key addition to existing and planned observing systems, including the international Global Climate Observing System and the Global Ocean Observing System. A number of 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 planned Atmospheric Radiation Monitor ground sites could effectively complement Climsat observations.

*Climsat rationale.* Present and future global climate change cannot be interpreted without knowledge of the changes in all significant climate forcings and radiative feedbacks. Some of these are not measured at all; some are being measured by the current observing system; but most are not being measured with sufficient precision. Climsat is a modest, small satellite program to monitor most of the missing forcings and feedbacks with high precision. As the record of changes in forcings and feedbacks lengthens, it will provide strong constraints on the interpretation of observed decadal climate changes, just as Keeling's CO<sub>2</sub> record has constrained interpretations of the carbon cycle.

*Climsat measurements.* Climsat will obtain well-calibrated Earth observations covering the solar and Earth emitted radiation spectra at spectral resolutions appropriate to long-term monitoring of climate forcings and feedbacks. Because climate forcings and feedbacks operate by altering these spectra, Climsat measurements will be able to detect "surprises", i.e., forcings and feedbacks we do not now know about, as well as known mechanisms. Although full exploitation of interferometric and polari-

metric measurements is a challenging research task, analyses should eventually become routine enough to be continued as part of the NOAA operational observing system, as was the case for CO<sub>2</sub> monitoring.

*Other climate measurements.* Climsat is not intended to provide all missing climate forcings. Measurements of changes in solar irradiance, which could be done from another small satellite, are also required. Several parameters monitored by Climsat, in particular properties of fine particles in the lower atmosphere, the vertical profile of ozone, and cloud microphysical properties, are very difficult to measure accurately, so that successful monitoring also will require long-term observations from selected ground sites and field campaigns for comparison of the satellite results with measurements made on or near the Earth's surface.

Another important research objective is diagnosis of the key heat and water transport processes that affect the sensitivity of climate. We particularly note the need to observe precipitation, ocean energy transports, and atmospheric heat and water vapor transports. Climsat generally will not address these difficult measurements. Experimental programs, similar to the Tropical Rainfall Measuring Mission, the World Ocean Circulation Experiment, and Acoustic Thermometry of Ocean Climate, must be continued and expanded upon to develop these capabilities. Operational observations of proven high accuracy, such as microwave temperature measurements, should be continued.

*Climsat status.* Congress allocated \$15M in 1991 to initiate Climsat on the basis of an article published in *Issues in Science and Technology* summarizing the proposed project. However, the Administration declined to undertake the project and the funding was later rescinded by Congress. Thus Climsat is currently a pre-project study without funding. We will continue discussions with the scientific community in the coming months and welcome any comments. We intend to request approval for a Climsat project in 1993. If it is approved, we anticipate a "Dear Colleague" letter or "Announcement of Opportunity" to solicit participation.

*Relation to EOS.* The Earth Observing System and Climsat are complementary, not competitive. EOS is well suited for detailed measurements which will be crucial for studying many global change processes, including some climate processes. But 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 has two identical satellites. 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 2003. Although there is a proposal to include two Climsat instruments on later EOS spacecraft, that plan is not budgeted, and thus of questionable realism; even if carried out, it would not satisfy the need for long-term homogeneous data with global coverage and diurnal sampling, and even this inadequate data would not be obtained until another decade or more.

*Data availability.* The Climsat data system will be configured to make calibrated measurements and data products widely available as they are produced, without a period of proprietary use by project participants.

*Educational outreach.* Climsat data and data products are well suited to contribute to teaching Earth sciences in schools because they will provide a low volume, comprehensive, on-going description of important climate parameters. Global maps of monthly-averaged distributions of surface and atmospheric properties will reveal seasonal and interannual changes which can be used to illustrate global change topics to students. Beginning researchers can analyze differences of intensity or polarization among wavelengths for particular regions or problems. These data volumes can be readily distributed over computer networks available in the mid-1990s. We intend to propose a liaison with educational organizations for this purpose as part of the Climsat program.

## WORKSHOP AGENDA

Workshop Objectives ..... Hansen

### SCIENCE OVERVIEW [moderator: Peter Stone]

Monitoring Issues From a Modeling Perspective ..... Mahlman  
 Forcings and Feedbacks of Long-Term Global Climate Change ..... Hansen  
 Climate Variability and the Ocean ..... Sarachik  
 Critique on Monitoring of Climate Diagnostics ..... Trenberth  
 Uncertainties in Global Temperatures ..... Karl  
 Accuracy Requirements for Climate Forcings and Feedbacks ..... DelGenio

### EXISTING MONITORING [moderator: Richard Somerville]

Operational Satellites, Including Pathfinder Data ..... Gruber  
 Stratospheric H<sub>2</sub>O ..... Rind  
 Tropospheric H<sub>2</sub>O -- Radiosondes ..... Elliott  
 Tropospheric H<sub>2</sub>O -- Satellites ..... Rabin  
 Tropospheric Aerosols -- Surface Station Network ..... Prospero  
 Tropospheric Aerosols -- CN/CCN Climatologies, WMO GAW Program ..... Gras  
 Clouds ..... Rossow  
 WMO Surface Radiation Network ..... Schiffer

### PROPOSED MONITORING [moderator: Marvin Geller]

EOS ..... Dozier  
 NOAA Monitoring Plans ..... Stowe  
 DoE/ARM ..... Stokes  
 Solar Irradiance ..... Lean  
 Aerosols -- station network ..... Schwartz  
 Ozone ..... McElroy  
 DoE small satellite ..... Vitko

### PROPOSED CLIMSAT MEASUREMENTS [moderator: Gerald North]

Rationale, Status Small Satellite Proposals ..... Hansen  
 SAGE III ..... McCormick  
 EOSP ..... Travis  
 MINT ..... Lacis

### ORBIT, SAMPLING REQUIREMENTS [moderator: Chuck Leith]

Overview, TRMM Experience ..... North  
 Sampling Tests Using ISCCP and GCM Data ..... Rossow

### PANEL DISCUSSION: Monitoring the Global Thermal Energy Cycle [moderator: Inez Fung]

Rationale for Analysis of Global Energy Cycle ..... Manabe, Wigley  
 Ozone ..... McElroy  
 Tropospheric Aerosols ..... Charlson  
 Stratospheric Aerosols ..... Hofmann  
 Water Vapor ..... Betts  
 Clouds ..... Wielicki

Agenda of the workshop, Long-Term Monitoring of Global Climate Forcings and Feedbacks, held at the NASA Goddard Institute for Space Studies on February 3-4, 1992.



## WORKSHOP SUMMARY

The workshop, Long-Term Monitoring of Global Climate Forcings and Feedbacks, was organized in two parts. Part I concerned the status of the science and current observations and Part II addressed a proposed series of small satellites (Climsat mission). The objective was to discuss the data needed to analyze the causes of long-term global climate change, in the context of existing and planned monitoring networks, and then to consider the potential of a small satellite system for supplying the missing climate data. Below we summarize both parts of the workshop and the consensus workshop conclusions.

### Overview of Science and Observations

In the opening paper, J. Mahlman stressed the importance of precisely calibrated long-term monitoring for emerging global change issues, and he noted the inadequacy of current measurement systems for monitoring purposes. The thesis of his paper was that a successful monitoring program can be put together only if there is a true *partnership* between the observational programs and the theory/modeling community. His bottom line was that we in the scientific community must step up to this difficult challenge, or we will all eventually be held accountable.

A proposed framework for analysis of global temperature change, focused on measuring all the major global climate forcings and radiative feedbacks over decades, was discussed by J. Hansen. Some of the forcings and feedbacks are presently measured, but others are not, or they are measured with inadequate calibration, or without plans for follow-ons to current instruments. The measurements must be continued for decades, because of the difficulty of separating unforced climate variability from naturally or anthropogenically forced climate changes. Even with accurate monitoring of all the forcings and feedbacks, ambiguity may persist in interpretation of temperature change, because of possible but unmeasured changes of atmospheric and oceanic energy transports. However, a long-term record of the forcings and feedbacks will provide a very strong constraint on interpretation of future global temperature change.

Existing long-term observations of key climate parameters were reviewed in a series of papers. Operational meteorological satellites are measuring a number of important climate parameters, but the instruments and calibrations were not designed with the objective of maintaining the precision needed to monitor decadal change. Nevertheless, there is value in extracting as much information as possible from available data, as described in the multi-agency "Pathfinder" data plans. Radiosondes have not reached their potential for long-term monitoring, because of lack of instrument calibrations and procedural standardizations among different countries. Surface stations have provided valuable data, but not generally with the continuity required for long-term monitoring. Several well calibrated satellite instruments exist, for example, solar measurements from UARS and ozone, stratospheric aerosol and water vapor measurements by SAGE II on the ERBS satellite, but there are no programs in place for a series of instruments to replace and continue these measurements.

Proposed climate monitoring was also reviewed in a series of papers. An update of NASA's planned Earth Observing System (EOS), which is the centerpiece of NASA's planned Mission to Planet Earth, was provided. Implications of recent budget reductions, including the elimination of EOS "hot spares", were described. Although such factors may impact the data continuity important to monitoring, it is clear that the detailed EOS data will be valuable for studies of climate processes. NOAA's plans for climate monitoring, including expected changes in future visible, infrared and microwave measurements, were described. The importance of solar irradiance monitoring was discussed, but there are no firm plans for long-term solar monitoring. The Department of Energy's plans for measurements related to clouds, radiation and climate change were described; these do not

include long-term monitoring. Plans for tropospheric aerosol and surface radiative flux measurements at a network of surface stations were presented, which would be an essential complement to global satellite monitoring.

### Climsat Proposal

The second day of the workshop was focused on consideration of the proposed Climsat mission, a series of small satellites designed for long-term monitoring of most of the climate forcings and feedbacks not otherwise being obtained with the required accuracy. Climsat is being studied by Goddard Space Flight Center in a pre-phase A stage, but it is not yet an approved project. If the project is approved for further development, it is expected that a Dear Colleague letter or Announcement of Opportunity will be issued to solicit participation in the further definition and implementation of the mission.

**Objective.** Monitoring of global radiative forcings and feedbacks will provide crucial constraints on our understanding of long-term changes of global temperature,  $\Delta T(t)$ , (Fig. S.1). The measurements must be continued for decades, because of the variability of  $\Delta T(t)$  and indications that much of the variability is unforced. But note that important conclusions can be obtained on shorter time scales, for example: (1) assessment of climate forcing due to ozone change versus forcing due to CFC change, (2) assessment of climate forcing due to anthropogenic tropospheric aerosol change versus forcing due to  $\text{CO}_2$  change, (3) short-term tests of climate models/ understanding (e.g., from volcanic aerosols).

**Inspiration.** Keeling's  $\text{CO}_2$  record (Fig. S.2) is a prototype of required high-precision long-term monitoring of global forcing/feedback parameters. The  $\text{CO}_2$  record can not by itself provide an understanding of either the global carbon cycle or the global thermal energy cycle, but it provides strong *constraints* on them. The  $\text{CO}_2$  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 the  $\text{CO}_2$  monitoring, after being proven as a research product, has become an operational activity of NOAA. Climsat monitoring, as  $\text{CO}_2$  monitoring, should be continued for decades, and it could become an operational activity once the approach is proven.

**Forcings and Feedbacks.** Table S.1 provides a framework for discussion of global climate forcings and feedbacks. The table also includes key climate diagnostics, but the proposed mission is concerned primarily with measurement of changes of forcing and feedback parameters over decades. Forcings are changes imposed on the planet's radiation balance, while feedbacks are radiative changes induced by climate change. As indicated by the first column of the table, some of the forcings and feedbacks are expected to be monitored adequately, but many are not. Accuracy requirements for these climate parameters have been estimated based on the need to detect changes believed likely to accompany a global warming of  $0.3^\circ\text{C}$  per decade, the rate of climate change estimated by the Intergovernmental Panel on Climate Change (IPCC).

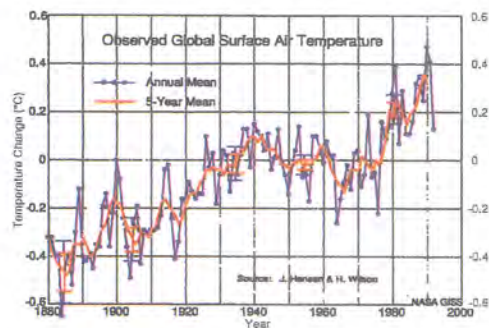


Fig. S.1. Observed global temperature.

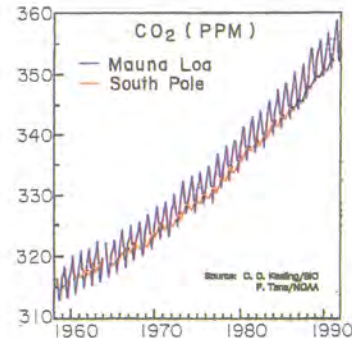


Fig. S.2.  $\text{CO}_2$  observations.

TABLE S.1. Principal Global Climate Forcings, Radiative Feedbacks, and Diagnostics

	1996 Calibrated Source Meeting Requirements	Proposed Climsat Contributions	Needed Complementary Data
<b>Climate Forcings</b>			
<b>Greenhouse gases</b>			
CO <sub>2</sub> , CFCs, CH <sub>4</sub> , N <sub>2</sub> O	G	—	—
O <sub>3</sub> (profile)	—	SAGE	NDSC
stratospheric H <sub>2</sub> O	—	SAGE	—
<b>Aerosols</b>			
tropospheric	—	EOSP (SAGE)	Surface reference network
stratospheric	—	SAGE (EOSP)	Surface reference network
Solar Irradiance	—	—	ACRIM, SOLSTICE
Surface Reflectivity	—	EOSP	—
<b>Radiative Feedbacks</b>			
<b>Clouds</b>			
cover	O	MINT/EOSP	—
height (temperature)	—	MINT/EOSP/SAGE	—
optical depth	—	MINT/EOSP	—
particle size	—	MINT/EOSP	—
water phase	—	MINT/EOSP	—
Lower tropospheric H <sub>2</sub> O (profile)	O, W	MINT	Reference radiosonde
Upper tropospheric H <sub>2</sub> O (profile)	—	SAGE/MINT	Reference radiosonde
Sea Ice Cover	O	—	—
Snow Cover	O	—	—
<b>Climate Diagnostics</b>			
<b>Temperature</b>			
upper air	W, O	MINT	Reference radiosonde
surface air	W	—	—
sea surface	S, O	MINT	—
<b>Ocean</b>			
internal temperature	—	—	Continuation of WOCE, acoustic tomography
surface salinity	—	—	Continuation of WOCE
transient tracers	—	—	Continuation of WOCE
<b>Radiation Budget</b>			
top of atmosphere	—	—	SCARAB, CERES
surface	—	—	WCRP Baseline Network

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. MINT = Michelson Interferometer.

Particularly noteworthy by their absence are adequate monitoring of the ozone profile, stratospheric water vapor, tropospheric aerosols, solar irradiance, surface reflectivity, critical cloud properties, and upper tropospheric water vapor. Without monitoring of these parameters it will be impossible to reliably attribute observed climate changes to causal mechanisms, or to provide decision-makers with a quantitative basis for judging such issues as the relative climate forcings of tropospheric aerosols versus greenhouse gases and ozone versus CFCs.

**Climsat Rationale.** Most of the missing climate parameters can be measured by three small instruments (Table S.1). These instruments measure with high precision the spectra of reflected solar radiation and emitted thermal radiation (Fig. S.3), and thus should encompass climate "surprises" as well as the known forcings and feedbacks, because any mechanism for climate change must influence these spectra. The key characteristic of the Climsat instruments is that they are each self-calibrating to a remarkable precision. This high precision is key to monitoring small decadal changes. All three instruments are based on proven technology, have predecessors with lifetimes exceeding 10 years, and are inexpensive. The instruments are small enough that Climsat can be launched by a Pegasus-class vehicle. Thus the cost of obtaining long-term (multi-decadal) datasets is not prohibitive.

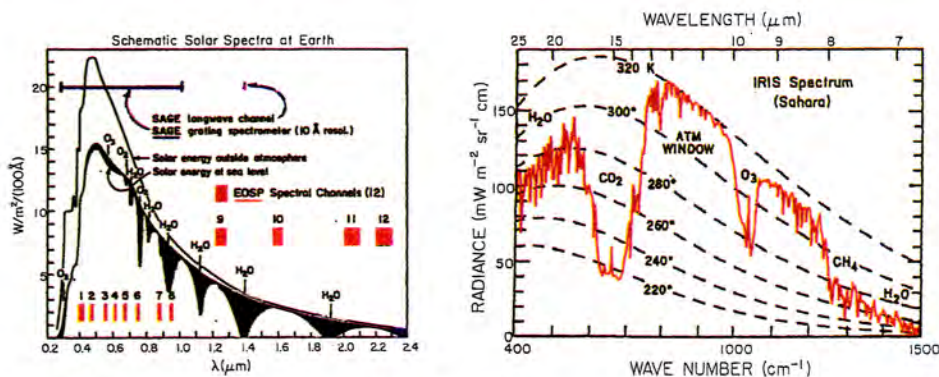


Fig. S.3. Approximate spectral regions covered by Climsat instruments; the infrared measurements will cover the range 250 to 1700  $cm^{-1}$ .

**Climsat Instruments.** SAGE, the Stratospheric Aerosol and Gas Experiment, observes the sun and moon through the Earth's atmosphere, obtaining precise vertical profiles of stratospheric aerosols, water vapor and ozone. The improved spectral resolution, higher sensitivity, and long wavelength detector of SAGE III, compared to predecessor instruments, will improve the accuracy of the data and extend the measurements deeper into the troposphere.

MINT, the Michelson Interferometer, makes a classical measurement with a modern instrument, precisely monitoring the infrared emission from the earth at high spectral resolution ( $2\ cm^{-1}$ ) over a broad spectral range ( $250\text{--}1700\ cm^{-1}$ ,  $6\text{--}40\ \mu m$ ). Such spectra are particularly suited for monitoring cloud properties (cloud cover, effective temperature, optical thickness, ice/water phase, and effective particle size) both day and night, and also tropospheric water vapor, ozone and temperature.

EOSP, the Earth Observing Scanning Polarimeter, measures the radiance and polarization of sunlight reflected by the earth in 12 spectral bands to very high precision. EOSP can accurately monitor the global distribution and nature of tropospheric aerosols, surface reflectance, and cloud properties.

**Orbit and Sampling Requirements.** Studies have been carried out using 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. The fewest number of satellites required is two, as indicated in Fig. S.4. A sun-synchronous near-polar orbiter provides a fixed diurnal reference. A precessing orbiter inclined  $50\text{--}60$  degrees to the equator provides a statistical sample of diurnal variations at latitudes with significant diurnal change. 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.

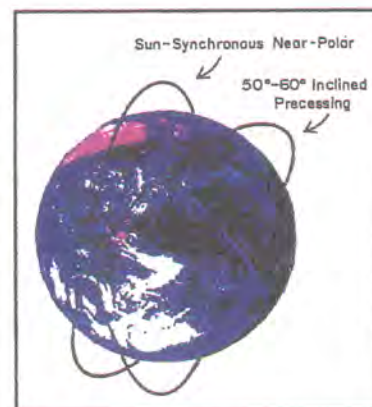


Fig. S.4. Climsat orbits.

**Needed Complementary Observations** The small satellite Climsat mission 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 Climsat 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; plans for such ground stations are under discussion, but require implementation.

## Workshop Conclusions

Following are conclusions of the workshop. These conclusions were not set down and agreed to at the workshop, but were developed from comments of participants on initial conclusions drafted by the report editors. These conclusions represent a consensus sense of the workshop discussions.

*1. Measurements of climate forcings and feedbacks are important for the purpose of understanding long-term climate change.*

It will be difficult, if not impossible, to interpret the causes of observed climate change in the absence of measurements of all the major climate forcings and feedbacks. Such data will not by itself permit complete diagnosis of climate change, but it will provide an important constraint on interpretation. Quantitative comparisons of different climate forcings also will have value for policymakers.

*2. Long-term continuous monitoring (several decades) of the climate forcings and feedbacks is an essential part of research on global change.*

There is strong evidence of substantial unforced climate variability, which implies the need for observations over decades at least in order to determine whether long-term, systematic changes are occurring. Data continuity is required because the climate system integrates the forcings over time. Temporal overlap of successive instruments also is needed for measurements dependent on transfer of calibration to maintain data record precision, for example: solar irradiance monitoring.

*3. Existing and planned observations will not provide measurements of all the major climate forcings and feedbacks over the appropriate time scales.*

Many of the climate forcings and feedbacks are either not being monitored or are being measured with inadequate accuracy for detecting small decadal changes. In some cases, data are now being obtained with sufficient accuracy, but there are no firm plans for continuation of the measurements.

*4. Climsat would be able to monitor most of the climate forcings and feedbacks not monitored by current and planned observation systems.*

A suite of three instruments on a pair of small satellites, one in a sun-synchronous polar orbit and the other in an inclined precessing orbit, would be able to monitor most of the missing climate forcings and feedbacks. The two satellites together provide both global coverage and a statistical sample of diurnal variations at latitudes with significant diurnal change. The two satellites also allow satellite-to-satellite transfer of calibration of the instruments if one satellite fails and must be replaced.

*5. Climsat needs to be supplemented by certain other programs to complete monitoring of the full set of forcings and feedbacks, specifically: solar monitoring from space, tropospheric aerosol and ozone profile monitoring from selected stations, and improved calibration of radiosonde measurements of tropospheric water vapor profiles. In situ field experiments are required to evaluate retrieval methods. The existing meteorological and planned ocean observing systems must also be maintained.*

The total solar irradiance and the ultraviolet spectrum are being measured from the UARS spacecraft, but there are no firm plans for continued monitoring. Aerosols, ozone and water vapor can all be measured by Climsat, but more detailed measurements, especially in the upper troposphere, are needed to provide "ground-truth" and more specific information.

***6. Climsat is complementary to the planned global change research program, including the EOS mission.***

Long-term monitoring of climate change is one key part of a comprehensive research program (cf., USGCRP Plan) which complements focused field projects and other satellite missions to understand climate system processes. EOS, with its larger number of instruments and higher spatial resolutions, is well suited for making the intensive measurements needed for climate process studies. Climsat is designed for long-term monitoring of climate forcings and feedbacks, including adequate diurnal sampling and transfer of calibration from satellite to satellite, at low cost so that repeat launches and continuous observations for decades are feasible.

***7. In the implementation of Climsat, it is important to strongly involve and support the relevant scientific communities.***

Representatives of the relevant scientific communities need to be involved in the detailed design of the monitoring system at the earliest stages, and a broader group should be funded to make use of the data products. Thus if a Climsat project is approved for development, there should be an Announcement of Opportunity to solicit involvement. Enhanced support of the relevant disciplines will be necessary to develop sufficient scientific knowledge and new talent for successful analysis of global climate change. The Climsat program should interact with students on levels from schools through universities by supplying data, analysis products, and cooperation required to aid Earth science education and research.



## PART I: SCIENCE AND OBSERVATIONS

### 1. Monitoring Issues from a Modeling Perspective<sup>1</sup>

*Jerry Mahlman, NOAA Geophysical Fluid Dynamics Laboratory*

#### Introduction

Recognition that earth's climate and biogeophysical conditions are likely changing due to human activities has led to a heightened awareness of the need for improved long-term global monitoring. The present long-term measurement efforts tend to be spotty in space, inadequately calibrated in time, and internally inconsistent with respect to other instruments and measured quantities. In some cases, such as most of the biosphere, most chemicals, and much of the ocean, even a minimal monitoring program is not available.

Recently, it has become painfully evident that emerging global change issues demand information and insights that the present global monitoring system simply cannot supply. This is because a monitoring system must provide much more than a statement of change at a given level of statistical confidence. It must describe changes in diverse parts of the entire earth system on regional to global scales. It must be able to provide enough input to allow an integrated physical characterization of the changes that have occurred. Finally, it must allow a separation of the observed changes into their natural and anthropogenic parts. The enormous policy significance of global change virtually guarantees an unprecedented level of scrutiny of the changes in the earth system and why they are happening.

These pressures create a number of emerging challenges and opportunities. For example, they will require a growing *partnership* between the observational programs and the theory/modeling community. Without this partnership, the scientific community will likely fall short in the monitoring effort.

The monitoring challenge before us is not to solve the problem now, but rather to set appropriate actions in motion so as to create the required framework for solution. Each individual piece needs to establish its role in the large problem and how the required interactions are to take place. Below, we emphasize some of the needs and opportunities that could and should be addressed through participation by the theoreticians and modelers in the global change monitoring effort.

#### Requirements for Theory/Modeling Support for Monitoring

**Context.** All observing systems are incomplete in the sense that they will never be able to measure everything, everywhere, all of the time with perfect accuracy and sustained calibrations. Moreover, even if this impossible goal could be achieved, the changes recorded by the "perfect" measurements would still need to be interpreted in the context of previous predictions and to be explained scientifically. Thus, the challenge before us is to seek the mechanisms by which models can be used in cooperation with observational systems to yield the maximum information and to produce the required synthesis.

**Information content of observational networks.** One of the most straightforward ways to utilize models in a monitoring context is in the evaluation of existing or hypothetical networks. For the atmosphere, successful studies conducted at GFDL have included evaluations of the global radiosonde

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<sup>1</sup> Much of this essay has been taken from Mahlman, J.D., 1992: Modeling Perspectives on Global Monitoring Requirements. Proceedings of the NOAA Workshop on "Assuring the Quality and Continuity of NOAA's Environmental Data," Silver Spring, MD (in press).



network, the Dobson total ozone network, global surface temperature measurements, and satellite temperature soundings. In such approaches, time-dependent, three-dimensional model output statistics are sampled in ways identical or similar to that of a given network. The advantage of using the model is that the "right" answers in this context are readily available for comparison against the answers inferred from the network subsample. Such research has revealed a number of significant deficiencies in the existing networks.

A frequent objection to using models for research in this context is that the models can be seriously incomplete depictions of reality. True enough. However, models have the virtue of constituting a *self-consistent* global dataset. Moreover, a typical model problem is that they produce only a restricted version of the much richer spatial and temporal structure found in nature. Thus, model diagnoses of network information tend to err on the conservative side; problems identified in networks through use of models are likely to be even worse in the real world.

*Evaluation of models from sparse observational data.* The other side of the coin is that even the current monitoring networks can be very powerful tools for evaluating strengths and weaknesses of models. Surprisingly, this is still true even for seriously undersampled quantities such as tropospheric ozone or oceanic salinity. It is a common misconception that 3-D global models can only be tested through use of complete 3-D global datasets. Just the opposite is true. Even *individual* local time series can (and often do) demonstrate that a global model is deficient in certain respects. This is because a global 3-D model attempts to capture both regional and global structures. Thus, if a global model exhibits local structure and temporal variations quite unlike the real world, the model has already been determined to be deficient. Thus, observed data properly taken at local sites can provide a powerful tool for model evaluation. In turn, improved models can provide a means for filling in the inevitable gaps in monitoring systems. We shall return to this theme below.

*Design of observational networks.* A particularly attractive possibility is to use models to design optimum networks at the outset. This concept is almost irresistible because of the prodigious expense of constructing and maintaining dense sampling networks. In principle, models can provide perspective and predictions on the value of data at various accuracies and sampling densities. In practice, this approach will be somewhat limited by the accuracy and credibility of the model employed. Models themselves undersample the environment because their data density is also limited by costs, in this case computational.

It is becoming increasingly common to hear that a new proposed monitoring network can be designed in advance using model-based insights. In principle, this is true; in practice, serious barriers remain. The most serious barrier seems to be the lack of properly focussed human talent. Each potential network design problem represents a serious and major research problem that typically requires several years of concentrated research to provide targeted, useful answers. Currently, there is a major deficiency of properly trained and focussed talent, backed by serious *commitment*, both personal and institutional, to solve such problems. The design of observational networks has the potential to become a significant new priority area in the context of global change monitoring and assessment.

*Model identification of global change "Fingerprints".* Questions regarding what the monitoring networks are capable of measuring are strongly influenced by the presence of an evolving theoretical/modeling perspective on what the expected changes *should* look like. Unfortunately, the issue is clouded by the presence of significant uncertainty in the model predictions. Even though they are uncertain, the model predictions still can provide major guidance to the kinds of signals that a network needs to be able to detect.

As examples, can the network detect a global warming signal in the ocean? Change in cloud-radiation feedbacks? How about CO<sub>2</sub> uptake changes? How will the warming signal differ from the expected low frequency variability operating on time scales similar to the expected anthropogenic climate signal? Can the signals be separated and understood independently?

An instructive example of the role of modeling in interpreting climate change can be seen in Figs. 1.1a-c taken from a 200 year integration of the low-resolution coupled ocean-atmosphere GFDL climate model. This is an integration which is in near perfect long-term statistical equilibrium and which incorporates no trends in climate forcing. Figure 1.1a for the Northern Hemisphere annual-mean surface air temperature shows trough-to-peak swings of nearly 0.5°C over time intervals of 40-60 years. These changes are of comparable magnitude to the observed changes in this century. Natural variability can either amplify or damp anthropogenically induced climate warming signals. Figures 1.1b and 1.1c show the same quantities but for the contiguous U.S. and for the "Washington, DC" gridbox (roughly 500 km on a side). These model results show how the natural variability increases dramatically as the region size decreases. An intelligent monitoring system must take such variability under careful consideration, particularly on time scales less than a decade or so.

Clearly, there are many questions that we cannot answer about climate change at this time. However, it is a very safe prediction that we will have to deal with them in the context of a global monitoring system. At the very minimum we must design our systems so that we at least deal with the difficult interpretative questions that are already before us. We must take on the natural variability question head on as a concomitant part of global change. We also must address the global sampling and long-term calibration question with sufficient skill to address adequately the proper monitoring identification of the regional climate change signals that are *already predicted for the climate/chemical system*. In many cases, the models are already predicting significant regional structures in the expected changes.

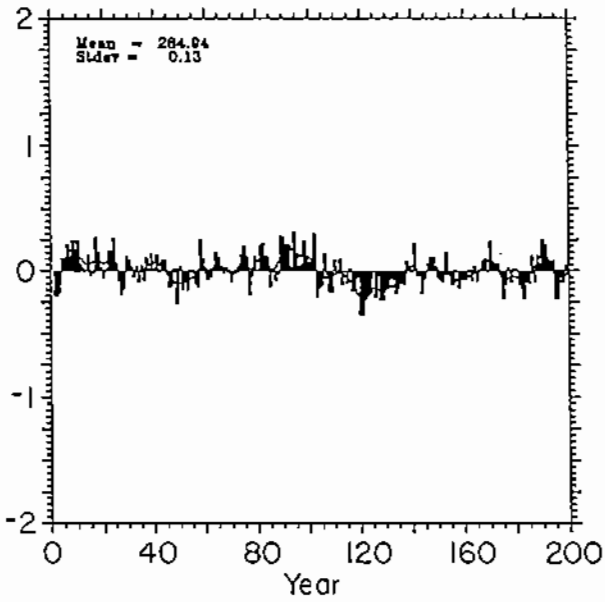
*Model assimilation of data in the context of climate change.* One of the inevitable aspects of expanded global monitoring systems is that they will be composed of data from heterogeneous sources. The data will be heterogenous in terms of types of instruments and the nature of the data obtained. The sampling will frequently be spotty in space and sporadic in time. The systems will be dynamically incomplete; temperature may be available, but winds and tropospheric ozone amounts may not be. Much of the data will be in the form of extended time series that contain gaps, errors, and calibration problems.

All of these data inconsistencies create the need for a unified approach for combining and synthesizing the data. Fortunately, over the past decade or so, viable approaches for accomplishing this have been developed for both the atmosphere and the ocean. This is the so-called four-dimensional data assimilation method (4DDA).

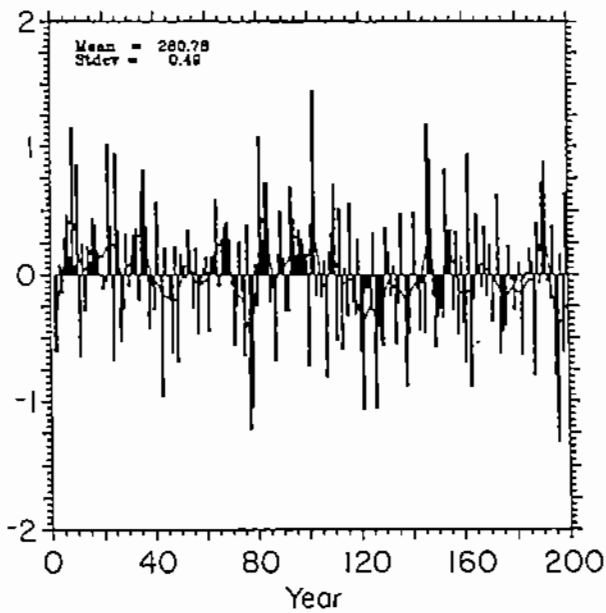
The 4DDA approach uses comprehensive numerical models to provide a physically consistent synthesis and global analysis. In effect 4DDA uses a global general circulation model to accept input data in a dynamically consistent manner. The model serves as a "traffic cop" determining which data in which forms are acceptable for inclusion. The data are incorporated in such a way as to "nudge" the model closest to a self consistent analysis of the data. In this context, the model serves also as a non-linear interpolator to fill in missing spatial and temporal information as well as missing variables (such as winds or trace constituents).

A great strength of this approach is the production of a self-consistent final analysis. A great weakness is that the quality of analysis can be quite sensitive to the quality of the model used. This is a particular concern for regions where the data coverage is extremely coarse and model quality remains relatively low. However, the insightful use of 4DDA techniques hold great promise to help improve the models as well as the data analyses.

(a) Northern Hemisphere



(b) United States



(c) Washington, DC

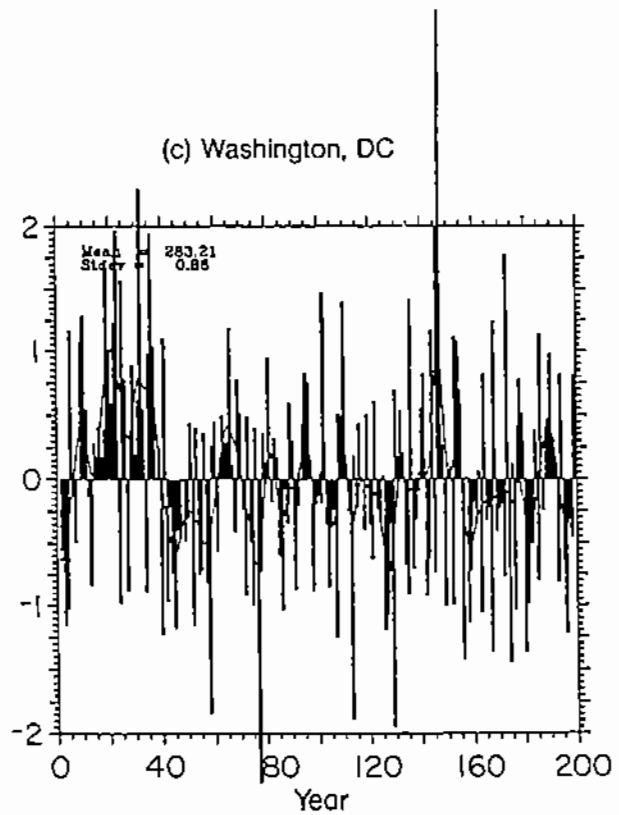


Fig. 1.1. Annual-average surface air temperature ( $^{\circ}\text{C}$ ) from a 200-year integration of the low resolution ( $\approx 500$  km grid spacing) coupled ocean-atmosphere GFDL climate model. This is a model in statistical equilibrium in which no trends in climate forcing are applied. (Courtesy S. Manabe and T. Delworth). Part (a) is for the Northern Hemisphere; (b) is for the contiguous U.S.; (c) is for the grid box encompassing Washington, DC.

In the monitoring context, perhaps the most promising use of 4DDA is in the retrospective analysis of historical datasets, such as is now in preparation at NOAA's National Meteorological Center. This approach may be able to yield analyses over decades that are appropriately time calibrated for monitoring use and evaluation. An unsolved problem with this approach is the limited ability of today's data checking procedures to filter out small apparent "trends" due to calibration drift or instrument changes. For a given analysis, this is a small effect; for climate change analysis, it can be as large as the signal itself. However, the advantage of the reanalysis procedure is that it can be redone as many times as necessary to glean the maximum information from the dataset. A major hurdle in reanalysis (and re-reanalysis) is that it is computationally and labor intensive. Obviously, there will be tradeoffs between the quality of the analyses and resources available, just as in the monitoring networks themselves.

### Final Comments

It is clear that success in the monitoring problem will require a growing partnership between theory/modeling and the observational data system. It is equally clear that the task will be extraordinarily difficult. It will take a long time, perhaps decades, and will require a new generation of scientific talent, institutional resolve, and financial resources.

Finally, some will counter argue that the problem is too difficult and too unglamorous to command the sustained resources and commitment required. When such counter arguments are advanced, it will be important to remember the challenge facing us all:

**We are faced with nothing less than the need to identify how the earth system is changing over the next century, explain why the changes are occurring, separate natural from anthropogenic change, and learn if our predictions were correct or incorrect.**

If we in the scientific community cannot step up to this challenge, it is a safe prediction that all of us will be held accountable.

## 2. Climate Forcings and Feedbacks

James Hansen, NASA Goddard Institute for Space Studies

### Overview

Global temperature has increased significantly during the past century (IPCC, 1990; Hansen and Lebedeff, 1987; Jones *et al.*, 1986), as illustrated in Fig. 2.1. 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. Climate forcings are changes *imposed* on the planet's energy balance, such as change of incoming sunlight or a human-induced change of surface properties due to deforestation. Radiative feedbacks are radiative changes induced by climate change, such as alteration of cloud properties or the extent of sea ice.

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 (Fig. 2.1), 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<sub>2</sub> 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 a large volcanic eruption or an El Niño.

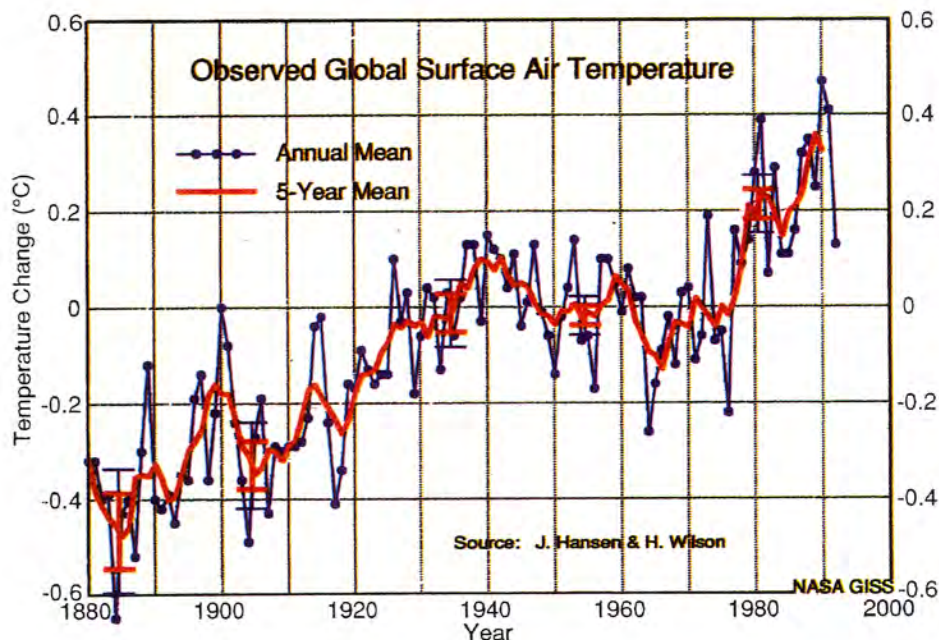
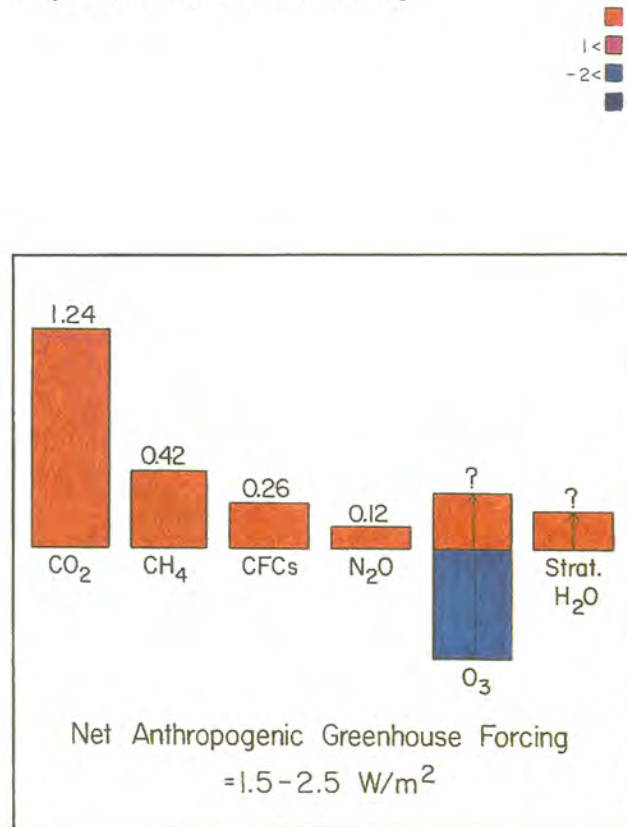


Fig. 2.1. Global surface air temperature change during the past century as extracted from measurements at meteorological stations (update of Hansen and Lebedeff, 1987).

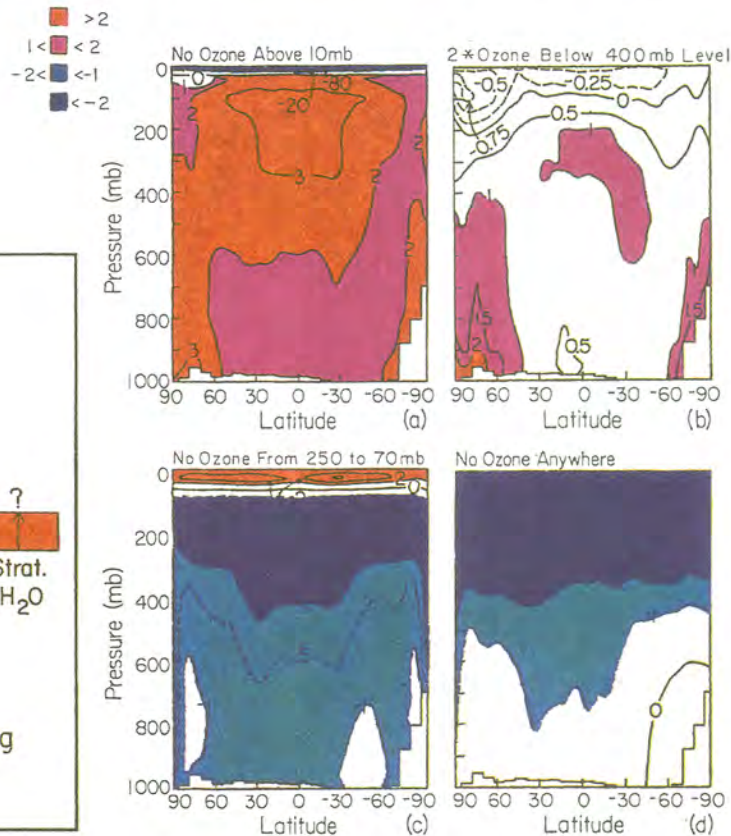
## Forcings and Feedbacks

**Greenhouse gases.** The measured increase of homogeneously mixed greenhouse gases since the beginning of the industrial revolution causes a climate forcing of about  $2 \text{ W/m}^2$  (IPCC, 1992; Hansen and Lacis, 1990; Dickinson and Cicerone, 1986; Ramanathan *et al.*, 1985; Wang *et al.*, 1976), as illustrated in Fig. 2.2. 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 may be increasing because of oxidation of increasing methane (Ellsaesser, 1983; Le Texier *et al.*, 1988), but other mechanisms are capable of influencing stratospheric water vapor, 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. These two mechanisms influence surface temperature in opposite directions and their relative importance depends on the altitude of the ozone change. Figure 2.3 illustrates the equilibrium response of a GCM to specific 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.



**Fig. 2.2.** Anthropogenic greenhouse climate forcings ( $\text{W/m}^2$ ) 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.



**Fig. 2.3.** Zonal mean equilibrium temperature change estimated for several arbitrary changes of the ozone distribution. Results were obtained from 50 year runs of the GISS GCM.

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, shown by the dashed curves in Fig. 2.4. Both of those ozone changes would cause surface heating. But limited ozone measurements in the 1970s (Tiao *et al.*, 1986; Reinsel *et al.*, 1984), shown by the histograms in Fig. 2.4, 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 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.

Lower stratospheric ozone loss can be a significant climate forcing. This is illustrated (Fig. 2.5) by comparison of the simulated global warming due to all the homogeneously mixed greenhouse gases (HMGG) with the simulated warming when ozone loss is also included. The ozone loss is that reported by Stolarski *et al.* (1991), with the assumption that the entire change is in the 70–250 mb region. The latter assumption probably maximizes the cooling effect of the ozone loss. Despite the large natural variability in the results of a single GCM experiment, or even the mean of 5 experiments, it is apparent that the ozone change is a significant contributor to the total greenhouse effect. Indeed, 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 ozone profile data are presently supplied by the SAGE II instrument on the ERB satellite, which is over eight years old. This data record can 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. Although total ozone abundance is being monitored by flights of the TOMS and SBUV instruments, there are no plans to fly SAGE III before 2002.

**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 an indirect climate forcing, by altering cloud properties. Existence of the latter effect is supported by satellite observations of increased cloud brightness in ship wakes (Coakley *et al.*, 1987), satellite observations of land-ocean and hemispheric contrasts of cloud droplet sizes (Han 1992), and

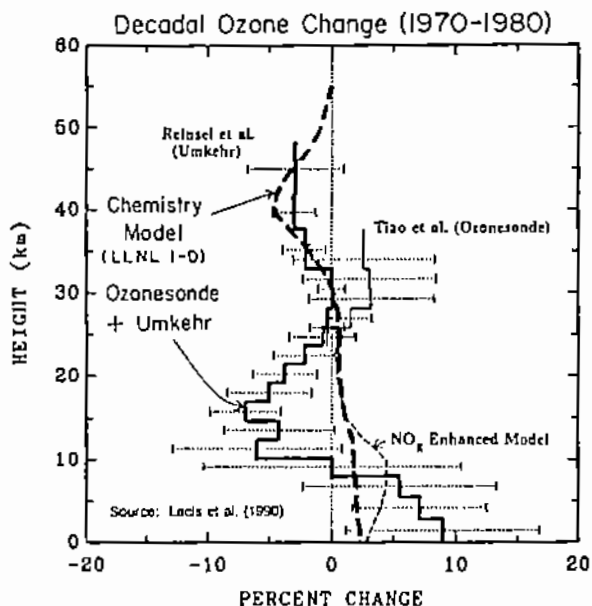


Fig. 2.4. Ozone changes predicted on the basis of homogeneous chemistry and ozone changes measured in the 1970s (figure reproduced from Lasis *et al.*, 1990).

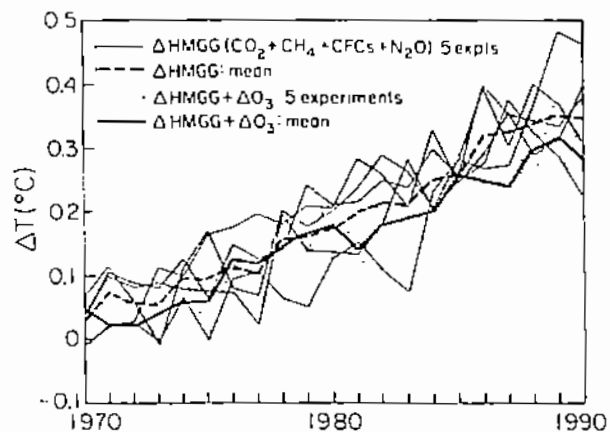
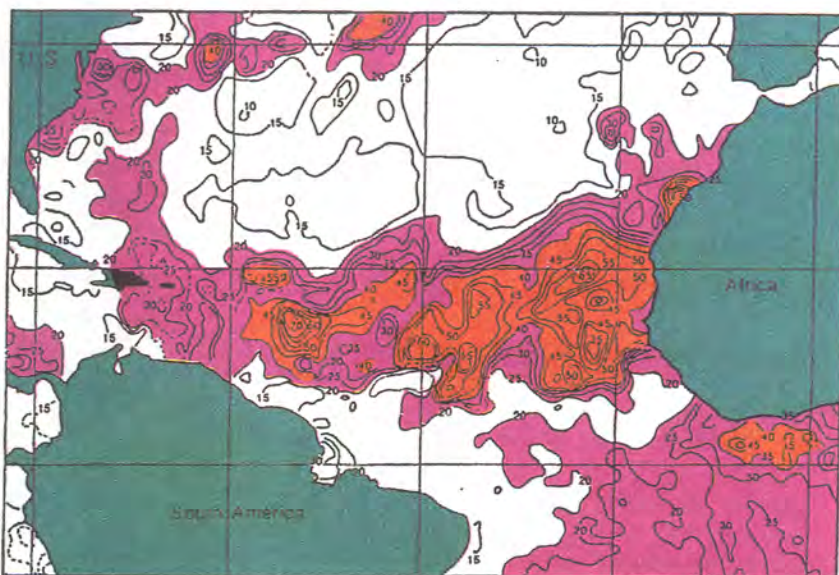


Fig. 2.5. Transient global temperature change due to changing greenhouse gases, as simulated with the GISS GCM (Hansen, 1991). Five experiments were run with only four homogeneously mixed greenhouse gases increasing ( $\Delta$ HMGG), and five additional experiments with ozone also changing ( $\Delta$ HMGG +  $\Delta$ O<sub>3</sub>). The ozone loss reported by Stolarski *et al.* was used with the loss placed entirely in the 70–250 mb region.



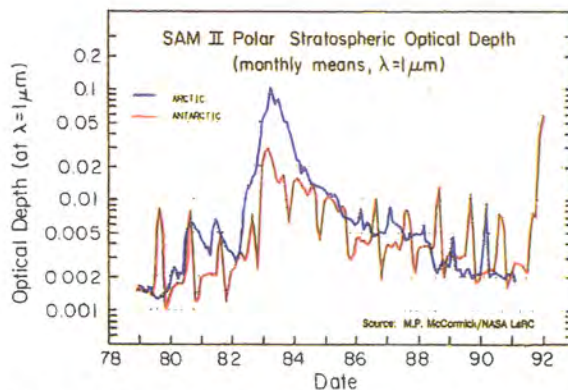
Source: L. STOWE/NOAA

**Fig. 2.6.** Estimate of aerosol optical depth ( $\times 100$ ) for June 18-25, 1987, based on reflected radiances measured by the AVHRR instrument on operational weather satellites (Rao *et al.*, 1988).

in situ data concerning the influence of the aerosol condensation nuclei on the clouds (Radke *et al.*, 1989). Sulfate aerosols originating in fossil fuel burning may produce a global climate forcing of order  $1 \text{ W/m}^2$  (Charlson *et al.*, 1991), and aerosols from biomass burning conceivably produce a comparable forcing (Penner *et al.*, 1992). Wind-blown desert dust has long been suspected of being an important forcing on regional climates (Tanre *et al.*, 1984; Joseph, 1984; Coakley and Cess, 1985). 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. Unfortunately, no global data exist that are adequate to define any of these aerosol climate forcings.

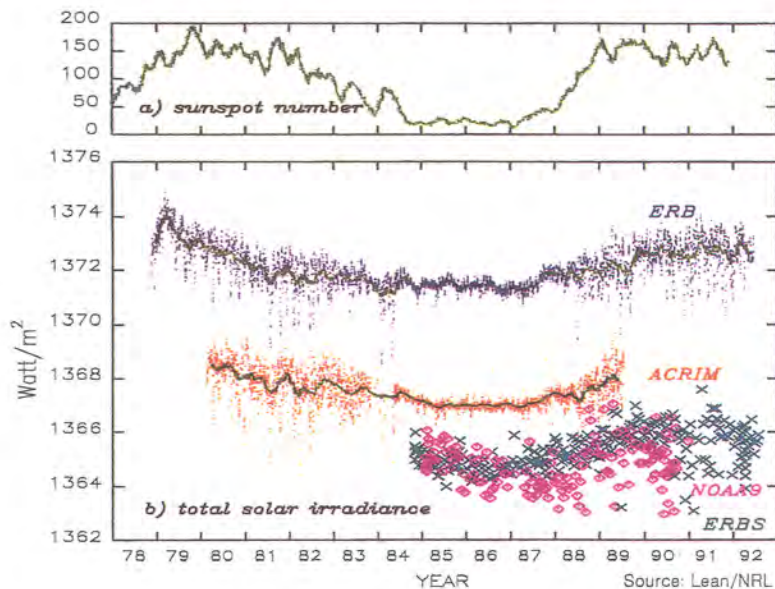
Aerosols can be seen in present satellite measurements (Rao *et al.*, 1988; Jankowiak and Tanre, 1992), as indicated by Fig. 2.6, which shows an estimate of aerosol optical depth based on the imaging instrument on an operational meteorological satellite. Sahara dust spreading westward from Africa is apparent, as well as sulfate aerosols moving eastward from the United States. However, the nature and accuracy of these data are inadequate to define the climate forcing, and, indeed, the optical depths in Fig. 2.6 are probably 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 has been monitored in the polar regions since late 1978 by a solar occultation instrument on the Nimbus-7 spacecraft (McCormick, *et al.*, 1979), as illustrated in Fig. 2.7. 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



**Fig. 2.7.** Stratospheric aerosol optical depth at  $1 \mu\text{m}$  wavelength in the polar regions measured by a solar occultation instrument on the Nimbus-7 spacecraft (M.P. McCormick, private communication).





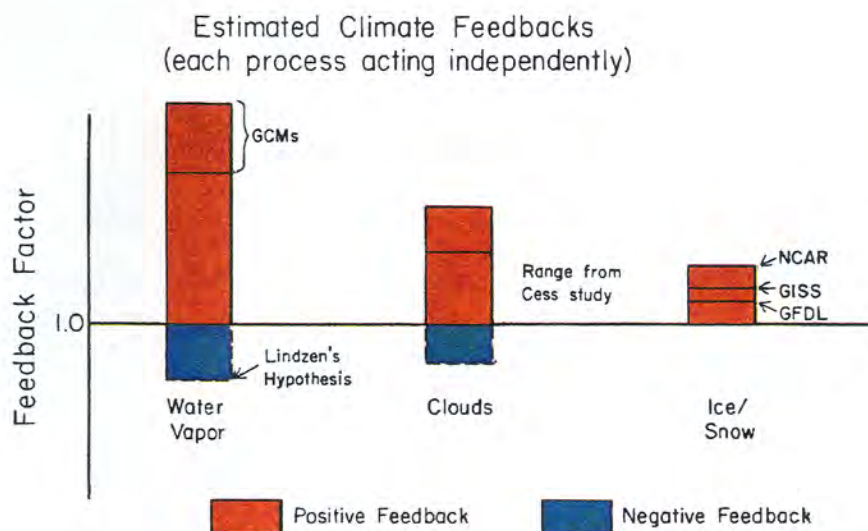
**Fig. 2.8.** Solar irradiance variations measured for the past solar cycle (J. Lean, private communication). The ACRIM results from the SMM and UARS missions, the latter not shown here, also have an offset from each other.

eruption in 1982 and the Mt. Hudson and Mt. Pinatubo eruptions in 1991. The approximate 50 percent 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  $2 \text{ W/m}^2$  (Hansen and Lacis, 1990), approximately the same as the forcing by all anthropogenic greenhouse gases, but opposite in sign. Although the aerosol forcing is more short-lived, it must be monitored if global temperature changes are to be interpreted. Nimbus-7 is nearing the end of its long life (launched in 1978), and it recently lost the ability to obtain occultation measurements in the Arctic. SAGE II has been obtaining data at low and middle latitudes from the ERB spacecraft since 1984, but that spacecraft is also showing signs of age and is already well beyond its design life. Flight of SAGE III is not planned before 2002.

**Solar irradiance.** Another potentially important climate forcing is change of solar irradiance. The spectrally integrated irradiance has been monitored for the past decade (Fig. 2.8), showing a decline of about 0.1 percent 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  $0.3 \text{ W/m}^2$  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 climate forcing varies strongly depending on the altitude of absorption. Note that there are offsets of the absolute irradiance even among the best calibrated instruments (Fig. 2.8), which implies the necessity of overlapping coverage by successive instruments for successful monitoring. There is no approved plan to continue monitoring of solar irradiance beyond the current UARS instrument (launched in late 1991 with an expected lifetime of 3–5 years).

**Surface reflectivity.** The next climate forcing mechanism likely 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 reduced the planetary albedo sufficiently to cause a cooling of about  $1^\circ\text{C}$  over the past few millennia, and may have been



**Fig. 2.9.** Schematic indication of the radiative feedback factors which have been found to determine the global sensitivity of the general circulation models to climate forcings such as doubled atmospheric  $\text{CO}_2$ .

responsible for the observed global cooling after 1940. Potter *et al.* (1981) calculated a smaller global cooling,  $0.2^\circ\text{C}$ , 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  $0.5 \text{ W/m}^2$ , 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.

**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: changes of atmospheric water vapor, clouds and the area of ice and snow cover (Cess *et al.*, 1989, 1990, 1991; Schlesinger and Mitchell, 1987; Hansen *et al.*, 1984). For example, for doubled  $\text{CO}_2$  the no-feedback climate sensitivity of  $1.2\text{--}1.3^\circ\text{C}$  is increased to about  $2\text{--}5^\circ\text{C}$  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 Fig. 2.9, 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 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.

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 seems unlikely that general agreement on the magnitude of global climate feedbacks can be obtained on the basis of models alone. 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.

#### Summary Caveat

It is appropriate to ask whether there are other important climate forcings or feedbacks, in addition to those which 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 very likely that there will be future surprises in our understanding of both climate forcings and feedbacks. Therefore, it is very 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.

### 3. Accuracy Requirements

*Anthony DelGenio, NASA Goddard Institute for Space Studies*

Satellite and surface measurements, if they are to serve as a climate monitoring system, must be accurate enough to permit detection of changes of climate parameters on decadal time scales. The accuracy requirements are difficult to define *a priori* since they depend on unknown future changes of climate forcings and feedbacks. As a framework for evaluation of candidate ClimSAT instruments and orbits, we estimate the accuracies that would be needed to measure changes expected over two decades based on theoretical considerations including GCM simulations and on observational evidence in cases where data are available for rates of change.

One major climate forcing known with reasonable accuracy is that caused by the anthropogenic homogeneously mixed greenhouse gases ( $\text{CO}_2$ , CFCs,  $\text{CH}_4$  and  $\text{N}_2\text{O}$ ). Their net forcing since the industrial revolution began is about  $2 \text{ W/m}^2$  (Fig. 2.2), and it is presently increasing at a rate of about  $1 \text{ W/m}^2$  per 20 years (Hansen and Lacis, 1990). Thus for a competing forcing or feedback to be important, it needs to be of the order of  $0.25 \text{ W/m}^2$  or larger on this time scale.

The significance of most climate feedbacks depends on their sensitivity to temperature change. Therefore we begin with an estimate of decadal temperature change. Figure 3.1 shows the transient temperature trends simulated by the GISS GCM when subjected to various scenarios of trace gas concentration increases (Hansen *et al.*, 1988). Scenario B, which represents the most plausible near-term emission rates and includes intermittent forcing by volcanic aerosols, yields a global mean surface air temperature increase  $\Delta T_s = 0.7^\circ\text{C}$  over the time period 1995-2015. This is consistent with the IPCC projection of about  $0.3^\circ\text{C}/\text{decade}$  global warming (IPCC, 1990). Several of our estimates below are based on this assumed rate of warming.

#### Climate Forcings

**Ozone.** Ozone changes have the potential to be a major climate forcing, for which rates of change can be estimated from recent observations. Change of total column ozone during the 1980s was monitored by the TOMS satellite instrument (Fig. 3.2; Stolarski *et al.*, 1991). But, as indicated

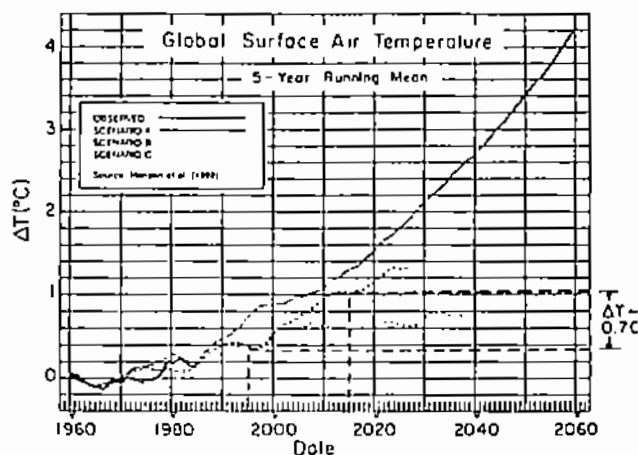


Fig. 3.1. Simulated global temperature change in climate simulations of Hansen *et al.* (1988). Rate of warming in the most realistic scenario (B), about  $0.3^\circ\text{C}/\text{decade}$ , is typical of other GCM and IPCC (1992) estimates.

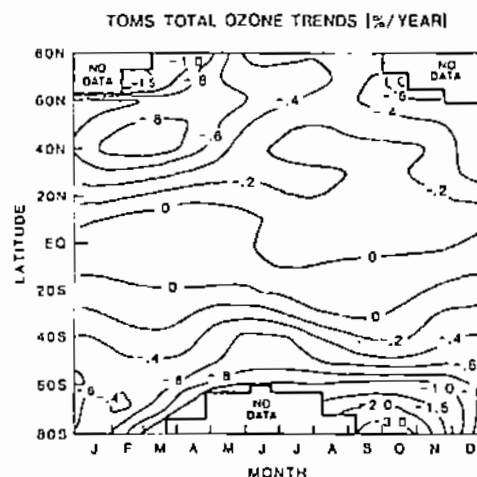


Fig. 3.2. Satellite (TOMS) observations indicate significant rate of total column ozone change during the 1980s (Stolarski *et al.*, 1991).

above (Figs. 2.2 and 2.3), the climate forcing due to the ozone change is entirely dependent on the vertical distribution of the ozone change. Data from a few mid-latitude ground stations suggest that the largest changes in the 1970s were near the tropopause (Fig. 2.4), and SAGE data for the 1980s suggest a qualitatively similar conclusion (McCormick *et al.*, 1992). The climate forcing by ozone depends mainly on the temperature of the ozone; as a result, it is required that the altitude of any significant ozone change be known within about 2 km in the troposphere and 5 km in the stratosphere. The magnitude of ozone change required to be significant is least at the tropopause, where changes of a few percent per decade are important, and increases toward both higher and lower altitudes.

**Stratospheric water vapor.** Doubling of stratospheric water vapor has been calculated to lead to a surface warming of the order of 1°C (Wang *et al.*, 1976), corresponding to a forcing of the order of 1 W/m<sup>2</sup>. Thus, if the long-term change of stratospheric water vapor is monitored to a precision of 10 percent, its climate forcing can be defined very accurately.

**Tropospheric aerosols.** Tropospheric aerosols are thought to contribute substantially to climate forcing, but the magnitude of their impact is highly uncertain due to an absence of adequate global observations. Both anthropogenic and biogenic aerosols have received attention for their possible roles in climate change. Anthropogenic SO<sub>2</sub> emissions have probably at least doubled the sulfate aerosol concentration of the atmosphere over the past century relative to the background natural concentration (Fig. 3.3; Charlson *et al.*, 1992). Global increases of 10-20%, and regional increases of 50% or more, over a 20-year period are plausible. Such global aerosol changes could cause a direct aerosol forcing conceivably as large as 0.5 W/m<sup>2</sup>, depending on the aerosol single scatter albedo, which would be comparable in magnitude to the expected climate forcing by anthropogenic greenhouse gases. Significant climate forcing from smoke due to biomass burning must also be considered (Penner *et al.*, 1992).

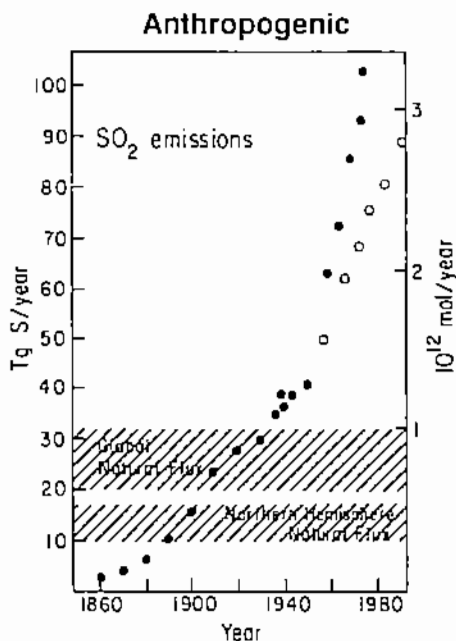


Fig. 3.3. Anthropogenic SO<sub>2</sub> emissions have probably at least doubled the sulfate aerosol concentration as evidenced by the above estimates for changes of SO<sub>2</sub> emissions. Open and filled circles represent data from two different sources (Charlson *et al.*, 1992).

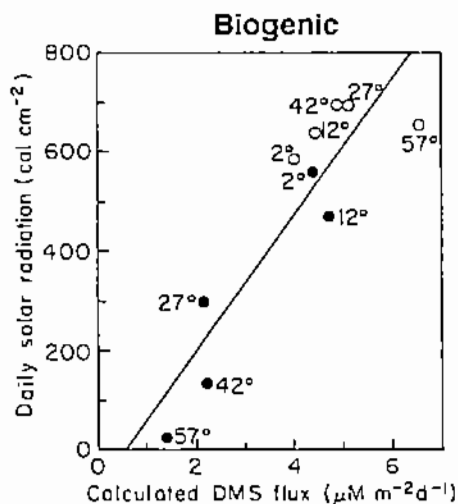


Fig. 3.4. Biogenic DMS emissions are sensitive to solar irradiance as evidenced by observed correlations between surface insolation and oceanic DMS flux (Bates *et al.*, 1987).

Biogenic emissions of dimethylsulphide (DMS) from the ocean appear to be sensitive to surface solar irradiance (Fig. 3.4; Bates *et al.*, 1987). Given the magnitude of measured solar luminosity variations (much less than one percent; Willson and Hudson, 1988) and the small variations in cloud cover and optical properties simulated by climate change models (Schlesinger and Mitchell, 1987), associated aerosol changes would be limited to a few percent over 20 years, much less than the anthropogenic component (Foley *et al.*, 1991). However, DMS emissions may also depend on other variable climate parameters, e.g., surface wind speed, in ways not currently documented. Climate forcing by a given aerosol optical depth is greater over the lower albedo ocean than over land; a change of global ocean aerosol mean optical depth of 0.01 is climatically significant (global forcing  $\sim 0.25 \text{ W/m}^2$ ). This change is an order of magnitude smaller than the accuracy or precision attainable with present satellite data.

The climate forcing by tropospheric aerosols depends on the aerosol optical depth, refractive index and size distribution, i.e., it is necessary to determine the aerosol microphysical properties (Patterson *et al.*, 1977; D'Almeida, 1987; Fouquart *et al.*, 1987; Tanre *et al.*, 1988; Leaitch and Isaac, 1991). A crucial parameter, which is very difficult to measure, is the aerosol single scatter albedo. One approach would be to infer the single scatter albedo by measuring the change of reflectance and aerosol optical depth together. The single scatter albedo needs to be known to an accuracy 0.02-0.03, which requires precision of the reflectance of the order of 0.01. Attainment of adequate knowledge of aerosol properties will require the combination of global satellite measurements supplemented by surface and in situ measurements for ground truth, as well as three-dimensional aerosol modeling.

Another major issue related to tropospheric aerosols is the changes which they may induce in cloud cover and cloud reflectivity. As an essential requirement for quantifying this climate forcing, the geographical distribution of aerosol microphysical properties must be monitored along with the cloud optical properties. The accuracy requirements for the measurements of cloud properties are described below.

**Stratospheric aerosols.** The climate forcing by stratospheric aerosols depends mainly on the visible optical depth of the aerosol layer, and secondarily on the aerosol size (Lacis *et al.*, 1992). Unlike the situation for the tropospheric aerosols, the forcing is practically independent of the amount of absorption by the aerosols (Lacis *et al.*, 1992). Addition of a visible optical depth of 0.15 causes a forcing of about  $4 \text{ W/m}^2$ , approximately the same as that for doubled  $\text{CO}_2$ , but in the opposite sense. Thus a significant climate forcing,  $0.25 \text{ W/m}^2$ , is caused by an optical depth of 0.01, which defines the required measurement accuracy. The effective radius of the aerosol size distribution needs to be known within about 50 percent.

**Solar irradiance.** A solar irradiance change of 2 percent, if spectrally flat, causes a climate forcing of  $4\text{-}5 \text{ W/m}^2$ , roughly equivalent to doubled  $\text{CO}_2$ . Thus a significant climate forcing would be produced by a solar irradiance change of about 0.1 percent, which defines the accuracy requirement for the integrated solar irradiance. However, climate forcing can also be caused by a change of the spectral distribution of the incoming radiation. The accuracy requirements are difficult to specify, because a change of the spectrum affects not only the amount and location of absorbed solar energy, but also may alter atmospheric composition, for example, ozone. The accuracies expected for the two spectral instruments on UARS, which monitor the sun in the ultraviolet region where the principal changes are known to occur, are probably sufficient, but measurements need to be extended to decadal time scales.

**Surface reflectivity.** A mean land reflectivity change of 0.1 is required to yield a forcing equivalent in magnitude to that for doubled  $\text{CO}_2$  (Hansen *et al.*, 1988). Thus a significant global climate forcing ( $0.25 \text{ W/m}^2$ ) could result from a long-term mean surface reflectivity change of about 0.006. Since the mean land surface reflectivity is about 0.2, the long-term precision needed for surface reflectivity monitoring is about 2 percent.

**Climate Feedbacks**

**Water vapor.** The single largest positive feedback in GCM estimates of climate sensitivity is due to water vapor, the water vapor concentration increasing as climate warms. Climate models with a variety of approaches to the parameterizations of moist convection and stratiform clouds agree that *relative* humidity changes in a warming climate will be small, of the order of a few percent (Cess *et al.*, 1990; DelGenio *et al.*, 1991; Fig. 3.5). This implies large changes of *specific* humidity, i.e., water vapor concentration. Like ozone and clouds, though, the vertical distribution of the change is also important (Arking, 1993). Indeed, Lindzen (1990) has speculated that changes in moist convection in a warming climate could actually dry the upper troposphere enough to eliminate or reverse the water vapor feedback. Although, as discussed in Section 2, a broad range of scientific evidence argues against the extreme proposition of Lindzen, this does not reduce the need to better quantify the nature of the water vapor feedback by means of long-term monitoring of the change of the water vapor profile.

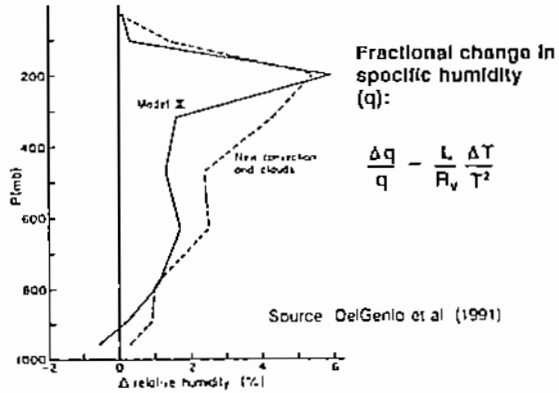


Fig. 3.5. Climate models with different approaches to the parameterization of convection and large-scale clouds yield similar responses of the water vapor profile to a change in surface temperature (DelGenio *et al.*, 1991).

If relative humidity changes are small, the Clausius-Clapeyron equation of thermodynamics can be used to estimate the change in specific humidity  $q$  from the change in saturation vapor pressure. The fractional change is  $\Delta q/q \approx L\Delta T/(R_v T^2)$ , where  $L$  is the latent heat of condensation,  $R_v$  the gas constant for water vapor, and  $T$  the temperature. For an assumed  $0.7^\circ\text{C}$  warming over 20 years, water vapor concentration would be expected to increase by about 4% (0.75 g/kg) near the surface and about 10% (0.001 g/kg) near the tropopause. Such a change of the water vapor profile, with everything else held fixed, would alter the net radiative flux at the tropopause or the top of the atmosphere by about  $0.5\text{-}1.0 \text{ W/m}^2$ , as indicated in Table 3.1.

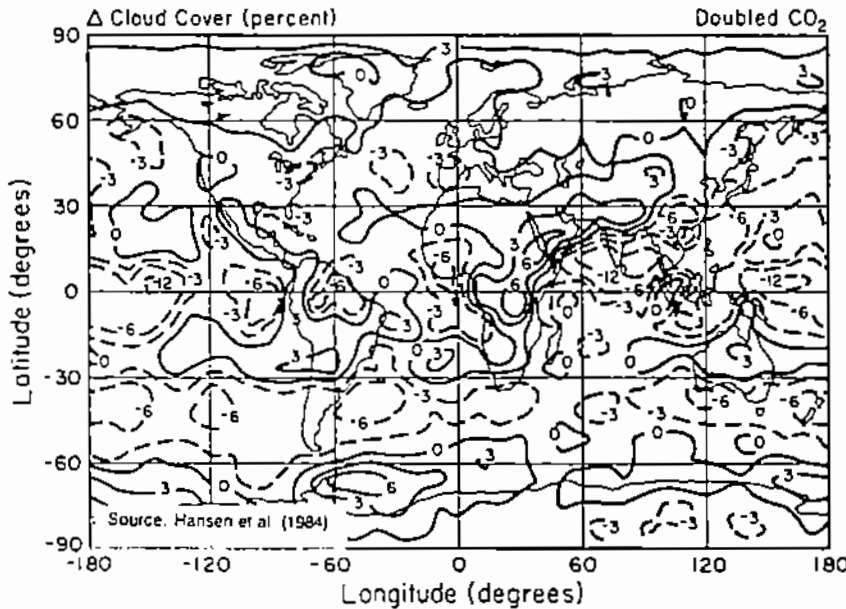


Fig. 3.6. Cloud cover changes in a doubled  $\text{CO}_2$  experiment with the GISS GCM (Hansen *et al.*, 1984).

**Cloud cover.** There is no fundamental understanding of whether cloud cover should increase or decrease as climate warms, since the change depends on the subtle balance between the competing effects of moisture and temperature changes. Nonetheless, virtually all of the available GCMs which have been subjected to either doubled  $\text{CO}_2$  (cf., Schlesinger and Mitchell, 1987) or a prescribed sea surface temperature anomaly (Cess *et al.*, 1990) predict that total cloud cover will slightly decrease as climate warms. The resulting cloud feedback on temperature is difficult to predict, because changes may be different for various cloud types, solar zenith angles, and underlying surface albedos. Simulated regional cloud changes are much larger than the global mean variation and may be of either sign (Fig. 3.6). Current GCMs suggest that over a 20-year period, global cloud amount may change by a fraction of a percent, with increases or decreases of 2-5% in different locations.

Ground-based observations of cloud cover (Henderson-Sellers, 1986, 1989; Karl and Steurer, 1990) suggest substantially larger variations over the past several decades, but the uncertainty in these observations is difficult to quantify. Satellite cloud observations (Rossow and Schiffer, 1991) show interannual global cloud changes of the order of a percent. A typical radiative flux change at the top of the atmosphere for a cloud cover change of 0.01 is  $0.25 \text{ W/m}^2$  (Table 3.1) which is another indication of the cloud cover accuracy desired of observations.

**Cloud height.** All presently available GCMs predict that the mean altitude of cloud tops will rise in a warmer climate (Fig. 3.7). There are several physical processes which influence the vertical distribution of clouds. In the tropics, for example, the dominant mechanism is deep moist convection, which supplies water vapor and ice for the formation of upper troposphere cirrus clouds and vents boundary layer water vapor that might otherwise form low-level stratus clouds. A simple estimate of the competing effects of boundary layer humidity and tropospheric lapse rate on convective stability and penetration depth (DelGenio, 1993) suggests that the altitude of tropical cirrus could rise by about 0.3 km (10-15 mb) in 20 years, given a  $0.7^\circ\text{C}$  surface warming. In midlatitudes, cloud height variations may be controlled additionally by changes in the strength and vertical scale of baroclinic waves. The change of cloud top level (and thus temperature) required to cause a change of  $0.25 \text{ W/m}^2$  of the net radiative flux at the top of the atmosphere, everything else held constant, is about 5 mb (Table 4.1).

**Cloud optical thickness.** Cloud optical thickness ( $\tau$ ) may be affected both by natural (i.e., thermodynamic and dynamic) and anthropogenic influences. Somerville and Remer (1984) used aircraft liquid water observations over the former Soviet Union to argue that low cloud optical thickness should increase by 4-5% per degree of temperature change. Theoretical arguments based on condensation in a lifted air parcel yield a similar result (Betts and Harshvardhan, 1987). Satellite data for the current climate confirm this finding over cold land areas, but suggest that at warm temperatures and especially over oceans, the optical thickness of low clouds may instead decrease with temperature, by as much as 10% per degree of warming (Tselioudis *et al.*, 1992). Thus, over 20 years with  $0.7^\circ\text{C}$  of surface

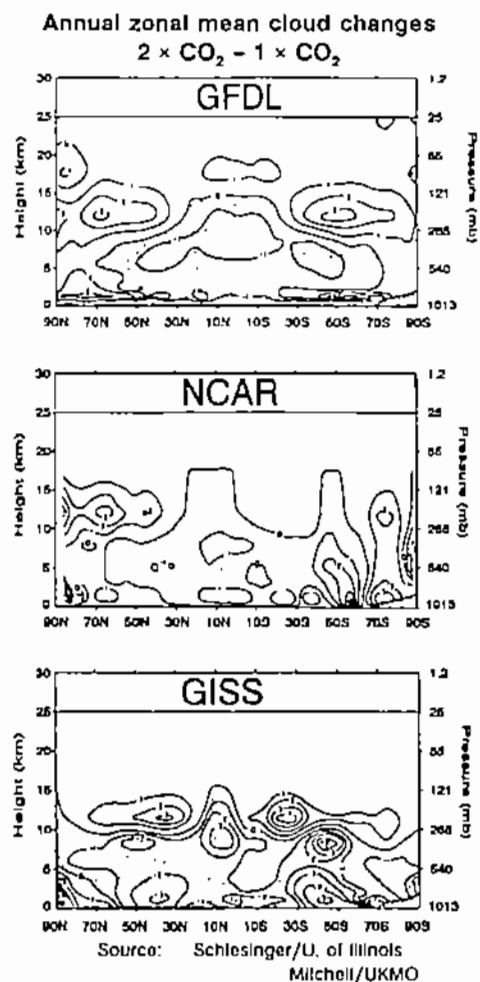


Fig. 3.7. Annual zonal mean cloud changes in equilibrium doubled  $\text{CO}_2$  experiments with three GCMs (Schlesinger and Mitchell, 1987).



warming, a typical low cloud with  $\tau = 10$  might experience an optical thickness change of about  $\pm 0.5$ . If thin cirrus ( $\tau \approx 1$ ) have similar temperature dependence, as suggested by the observations of Platt and Harshvardhan (1988), a much smaller change ( $|\Delta\tau| < 0.1$ ) would be projected for that cloud type.

Another mechanism for changing cloud optical thickness is increasing aerosols, which may provide additional cloud condensation nuclei (CCN) for cloud droplet formation, especially over the remote oceans where droplet formation is most limited by the availability of nucleation sites. The effects are twofold. Increasing aerosols may translate into increasing droplet concentration and therefore decreasing droplet size, directly affecting cloud reflectivity (Twomey *et al.*, 1984). For example, if cloud liquid water content remains constant and if the fractional increase in droplet concentration is 70% as large as the increase in aerosol concentration (Kaufman *et al.*, 1991), the 50% regional increase in anthropogenic aerosols discussed above would imply a low cloud optical thickness increase of  $\Delta\tau \approx 1$ . Furthermore, smaller droplets precipitate less readily, suppressing an important sink of cloud water and thus further increasing cloud optical thickness (Albrecht, 1989). Where these effects occur, relative to the thermodynamic/dynamic controls mentioned previously, will influence the magnitude of the optical thickness changes. Quantitative analysis of the role of cloud optical thickness changes will require both global monitoring and in situ process studies.

**Cloud particle size.** Changes of cloud particle size are intimately involved in most mechanisms for change of cloud optical thickness. Although it is the change of optical thickness which is the immediate "cause" of a change of radiative balance, and thus of the climate forcing or feedback, it is important to measure the change of cloud microphysics. It is only with such knowledge that we are likely to obtain an understanding of the causes of any long-term changes of cloud radiative properties which affect climate sensitivity.

Cloud particle size changes are the result of the competing influences of changes in cloud water content and droplet concentration. In the absence of aerosol impacts, and ignoring sinks of cloud water such as precipitation and entrainment of clear air, the temperature dependence of adiabatic liquid water content (Betts and Harshvardhan, 1987) implies an increase in effective radius of only about  $0.1 \mu\text{m}$  over 20 years. On the other hand, for a 50% regional increase in tropospheric aerosols, effective radius would be expected to decrease by approximately  $1 \mu\text{m}$ . Size changes that large have been detected in ship tracks (Radke *et al.*, 1989) and between land and ocean clouds and northern and southern hemisphere clouds (Han, 1992). Determination of the climatic significance of this mechanism for cloud particle size change requires long-term global observations.

### Radiative Impacts

The plausible changes over a 20 year period of the different climate forcing and feedback parameters discussed above can be readily converted to an approximate radiative flux change at the top of the atmosphere, all other factors being held fixed. The results of such computations are shown in the third column of Table 3.1, based on a radiative model employing the global datasets of the ISCCP project. The flux changes range from a few tenths of a  $\text{W}/\text{m}^2$  to several  $\text{W}/\text{m}^2$ . These fluxes define the minimum accuracies that would be required for a global monitoring system. It is apparent that many of these fluxes are comparable in magnitude to the approximate  $1 \text{ W}/\text{m}^2$  climate forcing which is anticipated to occur in the next 20 years due to continued increases of the homogeneously mixed greenhouse gases,  $\text{CO}_2$ , CFCs,  $\text{CH}_4$  and  $\text{N}_2\text{O}$  (IPCC, 1992; Hansen *et al.*, 1988; Ramanathan *et al.*, 1985). The regional cloud changes are expected to be reduced on global average.

Ideally, a monitoring system for climate forcings and feedbacks would be capable not only of detecting changes of the magnitudes indicated in the first column of Table 3.1, but would measure any changes capable of yielding a significant forcing or feedback. We define a significant long-term global mean flux change as  $0.25 \text{ W}/\text{m}^2$  or greater, based on the  $1 \text{ W}/\text{m}^2$  forcing due to anticipated

**TABLE 3.1. Effect of anticipated parameter changes on radiative balance. Summary of anticipated or plausible changes of radiative quantities over a 20 year period (second column) as discussed in the text. The corresponding change in the net radiative flux at the top of the atmosphere is given in the third column, as estimated with a radiative model employing the global datasets of the ISCCP project.**

<u>Forcing or Feedback</u>	<u>Anticipated Change of Quantity in 20 Years</u>	<u>Corresponding <math>\Delta</math> Flux at TOA (W/m<sup>2</sup>)</u>
Ozone	$\frac{\Delta O_3}{O_3} =$ several percent or more	Latitude and Height-dependent
Tropospheric aerosol	$\Delta \tau = 0.04$	-1.0
Stratospheric H <sub>2</sub> O	$\frac{\Delta q}{q} = 0.3$	+0.3
Surface albedo	$\Delta A_g = 0.01$ (land)	-0.4
Tropospheric H <sub>2</sub> O upper lower	$\frac{\Delta q}{q} = \begin{cases} .10 \\ .04 \end{cases}$	+1.1 +0.5
Cloud cover cirrus stratus	$\Delta C = \begin{cases} 0.03 \text{ (regional)} \\ 0.03 \text{ (regional)} \end{cases}$	+2.0 -3.0
Cloud top pressure	$\Delta p = -12$ mb	+0.6
Cloud optical thickness cirrus stratus	$\Delta \tau = \begin{cases} 0.1 \\ 1 \end{cases}$ (regional)	+1.4 -3.8
Cloud particle size	$\Delta r = -1$ $\mu\text{m}$ (regional)	-1.4

increases of greenhouse gases in the next 20 years. The constituent changes required to yield such flux changes are considered in Section 7 (Table 7.4). Many of these physical parameter changes are quite small. Nevertheless, we find that the potential exists for long-term monitoring of the climate forcings and feedbacks to precisions close to or exceeding even these more difficult requirements.

#### 4. Summary of Science Overview Session

*Peter Stone, Massachusetts Institute of Technology*

The Workshop's first session was devoted to an overview of the science of long-term global change, and what type of observations are needed to help understand how the climate system works, what changes are taking place, and what is causing them. Although the workshop's principal objective concerned the global thermal energy cycle, the presentations in the first session focused on understanding both the system's heat and moisture budgets. A starting point for the discussions was provided by the summary of important climate parameters (Table S.1), which had been presented by J. Hansen in his opening remarks for the workshop. Several speakers emphasized the importance of parameters not included in Table S.1, for the purpose of understanding climate change.

J. Mahlman (NOAA/GFDL) opened the session with a discussion of climate monitoring issues from a modeling perspective, as summarized in his essay (Section 1). Mahlman argued convincingly that in the near future advances in our understanding were most likely to come through a synthesis of (incomplete) observations, theory, and modeling.

J. Hansen (NASA/GISS) pointed to uncertainties in our understanding of climate forcings and feedbacks, especially our lack of knowledge about the forcing associated with changes in atmospheric aerosols, the ozone profile, and stratospheric water vapor, and our ignorance about the feedbacks associated with clouds and upper tropospheric water vapor. There was widespread agreement that accurate monitoring of these quantities would provide valuable checks on our climate modeling capabilities, and significantly enhance our understanding of global scale climate sensitivity.

E. Sarachik (University of Washington) noted that understanding the ocean component of the climate system requires a knowledge of all the surface fluxes between the atmosphere and oceans, i.e., momentum, sensible heat, moisture, radiation, and trace gases. K. Trenberth (NCAR) noted the importance of dynamical fluxes of heat and moisture and pointed out that to understand the global energy cycle, one would like to measure *all* the components and fluxes. He also suggested that our knowledge of atmospheric transports could be improved by re-analyzing archived data. T. Karl (NOAA/NCDC) suggested that ground-based measurements of global temperatures could be greatly improved by standardizing all aspects of the observations and analysis, and by optimizing the station network.

A. DelGenio (NASA/GISS) made estimates of the magnitudes of changes of climate forcings and feedbacks that might occur over a twenty-year period, and that we would like to measure. Many of them are inherently very small. Some examples are a global mean surface temperature increase as much as 0.6-0.7 K, ozone changes ~10%, upper tropospheric water vapor changes  $\sim 10^{-3}$  g/kg, and global cloud cover changes of the order of 1%. Many speakers pointed out that achieving the required degree of accuracy is often very difficult because many climate parameters have a high degree of spatial and temporal variability, a subject addressed quantitatively later in the workshop. There was general agreement that to obtain data useful for climate it is essential that the measurements be carried out continuously for decades, that the instruments be accurately and consistently calibrated, and that diurnal variations be resolved.

At the same time it was generally recognized that not all the desired measurements would or could be made in the foreseeable future. Examples of measurements that are unlikely to be made are measurements of changes in turbulent surface fluxes of heat and moisture, changes in the structure of the deep oceans, changes in the dynamical transports in the atmosphere and oceans, and changes in the net radiative forcing of the global climate system. However, it was agreed that accurate monitoring of changes of each of the individual global climate forcings and feedbacks in Table S.1 would provide a valuable constraint on interpretation of future climate change.

## 5. Summary of Session on Existing Monitoring

*Richard Somerville, Scripps Institution of Oceanography*

A substantial amount of data on global climate forcings and feedbacks is already being obtained. Although many of the measurement systems were not intended for long-term climate monitoring purposes, they provide valuable experience and lessons, as well as datasets. The workshop presentations on existing monitoring are summarized here.

***Forcing and Feedback Variables from Operational Satellites.*** A. Gruber (NOAA/NESDIS) discussed how remote sensing data from observational meteorological satellites can contribute to monitoring climate forcing and feedback variables. The operational instruments include AVHRR, TOVS, SBUV, GOES VAS and SSM/I. As one spectacular example of the utility of these measurements, the AVHRR aboard the NOAA-11 satellite measured the changes in stratospheric aerosol optical thickness following the June 1991 eruption of Mt. Pinatubo. The satellite radiances at  $0.6 \mu\text{m}$  wavelength showed the volcanic cloud encircling the earth in three weeks and gradually spreading into higher latitudes from its origin in the tropics. Preliminary estimates, based on the AVHRR data, were that the globally averaged net radiation at the top of the atmosphere might be reduced by  $2.5 \text{ W/m}^2$  over two to four years, thus providing climate modelers with a potentially challenging natural validation experiment.

The TOVS infrared observations of total column ozone have been invaluable in providing independent measurements which complement the ultraviolet data from other sensors. Because the NOAA instruments overlapped for more than a year in 1985-86 with the earlier SBUV data, a consistent and continuous record of total ozone exists since the launch of Nimbus-7 in late 1978. Advantages of the TOVS instrument include a day/night capability and in-flight calibration.

Problems encountered in using operational (and many research) satellite instruments to detect long-term change include drift in both observation time-of-day and sensor calibration. Additional anomalous effects can be severe, such as the effect of aerosols on space-based infrared estimates of sea surface temperature. Operational changes from one satellite to its successor can sometimes compromise the integrity of long-term time series. Nevertheless, operational satellite remote sensing has great potential for climate monitoring. One particularly important area is that of determining cloud parameters, such as cloud amount and cloud top pressure, by techniques other than those used by research satellites. It is especially encouraging that a number of operational products should soon be conveniently accessible to the research community in the pre-EOS time frame as Pathfinder datasets. These sets, each more than a decade long, include AVHRR, TOVS, VISSR and VAS.

***Satellite Stratospheric Water Vapor Measurements.*** D. Rind (NASA/GISS) discussed the critical problem of measuring stratospheric water vapor from space. Climate theorists agree that this quantity is among the most important and most poorly known parameters affecting global climate change. The SAGE II instrument, which has been flying since 1984, has produced invaluable data, including the beginnings of a credible global climatology of stratospheric water vapor. Detailed intercomparisons have been carried out between SAGE II and two short-lived space-based sensors, LIMS on Nimbus-7 in 1978-79 and ATMOS on Spacelab 3 in 1985. SAGE II measurements of tropospheric water vapor also compare well with colocated radiosondes as well as with other remote sensing data. The potential of the SAGE II approach to contribute to stratospheric water vapor monitoring is excellent.

***The Global Radiosonde Network.*** W.P. Elliott (NOAA/ARL) summarized the characteristics of the global radiosonde network which are most relevant to climate monitoring. As is well known, a severe limitation of the network as a climate system is the poor geographical distribution of reporting stations. Only portions of North America and the Eurasian land mass are adequately

sampled. Coverage over land in the tropics and the Southern Hemisphere is marginal at best, and all of the world ocean is poorly represented. Worldwide, only about 700 radiosonde stations report regularly, although more stations exist, and some of the 700 stations report several times a day.

Creating a consistent and homogeneous dataset from radiosonde data is a task with many pitfalls. More than 15 different radiosonde instruments are currently in use, although recently two manufacturers (Viz in the United States and Vaisala in Finland) together appear to have about 75% of the market. Interestingly, differences in relative humidity measurements between instruments made by these two companies may be due in large part to analysis software rather than to the sensors themselves.

In the lower troposphere, the better radiosondes can achieve a one-sigma precision of about 0.2°C in temperature and 3.5% in relative humidity. For typical conditions, this implies that the comparable figures for calculated quantities are approximately 1° for dewpoint, 0.5 gm/kg for specific humidity and 5 to 10% for column water vapor or precipitable water. In principle, a "reference radiosonde" could be developed with higher-quality sensors. It would cost more than operational sondes, but could be co-flown with them and used to intercalibrate and compare the heterogeneous population of sondes, both present and past. Such an effort might well be worthwhile, enabling the extraction of uniquely valuable climate data from the long radiosonde record at a relatively modest cost. The process of improving the radiosonde is a continuing one for the operational services, but it introduces sources of bias into the climate record, and it is critical that these be recognized and taken into account.

*Analyzing Regional Climate Using Satellite Imagery.* R. Rabin (NOAA/ERL/NSSL) presented a case study carried out by himself and several colleagues (C. Hayden, G. Wade, and L. McMurdie) involving analysis of the atmosphere over the Gulf of Mexico, with emphasis on SSM/I and VAS measurements of total precipitable water and SSM/I measurements of surface wind speed. These satellite remote sensing data, in conjunction with a high-resolution numerical weather prediction model, made it possible to construct a consistent four-dimensional moisture budget for the region.

*Sampling Networks for Measuring Aerosol Species.* J. Prospero (University of Miami) presented a description of aerosol sampling network operated by the University of Miami. The purpose of this network is to develop a chemical climatology of the major aerosol species. The principal species include sulfate, methanesulfonate, nitrate, ammonia, sodium, and minerals. The long-term goal of the program is to characterize the distribution of these species in the atmosphere over the ocean and to understand the factors that control aerosol concentration, i.e., sources, transport and removal. The experimental strategy for the network includes establishing stations on the coasts of islands and continents in the major ocean regions, with continuously operating instruments. The samples are analyzed in Miami. In addition to climatological sampling, intensive experiments are carried out to address questions of aerosol size, gas-aerosol relationships, and synoptic issues. Results were shown from the Pacific, the Atlantic, and the Antarctic.

*Measurements of Condensation Nuclei.* J. Gras (CSIRO/DAR) summarized efforts to characterize cloud condensation nuclei in several locations. These include the Antarctic Aerosol Program in the Southern Ocean. Currently, the available network is inadequate to establish a global climatology of condensation nuclei. The Global Atmospheric Watch is a WMO program with eight existing "global" stations, of which five currently have active aerosol programs. Additionally, of 80 "regional" stations, only three have aerosol programs. Because of recent interest in potentially important climate feedback processes involving cloud condensation nuclei, it is hoped that a systematic aerosol measurement program can be established by augmenting this existing network.

*Measurements of Clouds and Cloud Properties.* W. Rossow (NASA/GISS) surveyed the available sources of observational cloud data, with emphasis on ISCCP. He pointed out that while the satellite remote sensing measurements have the advantage of better spatial and temporal resolution and areal coverage, other approaches have unique advantages of their own. For example, the surface network has the longest record, radiosondes and lidars can provide vertical structure information, and field experiments can elucidate details of physical processes. ISCCP has provided global monitoring of cloud amount, cloud top pressure, and cloud optical thickness. Among the variables which cannot be observed adequately at present, polar cloudiness, thin boundary layer cloudiness and cirrus properties are among the most important. Cirrus clouds are emerging as potentially key elements in the climate puzzle, and future efforts should be directed at measuring quantities such as the diurnal cycle of thin cirrus, the frequency of simultaneous occurrence of cirrus and low clouds, and the microphysical properties of ice clouds.

*The Baseline Surface Radiation Network.* R. Schiffer (NASA Headquarters) outlined the mission of a baseline surface radiation network. This network is intended to monitor long-term trends in surface radiation fluxes, to validate satellite measurements, and ultimately to lead to an improved understanding of the effects of clouds, water vapor and aerosols on the planetary radiation balance. Estimated measurement accuracies for the major components of the surface radiation budget range between 10 and 30 W/m<sup>2</sup> at present, and it is hoped that these figures will be reduced to around 5 W/m<sup>2</sup> in about 5 years.

## 6. Summary of Session on Proposed Monitoring

*Marvin Geller, State University of New York (Stony Brook)*

A considerable number of satellite measurements of the climate system are planned for the remainder of this century and the beginnings of the next, as well as some complementary non-space measurements. Presentations were made on several of these, as summarized here.

**EOS.** J. Dozier (University of California, Santa Barbara), Senior EOS Project Scientist, gave an update on NASA's Planned Earth Observation System (EOS) in the context of planned future space observations of the Earth system. EOS is clearly the planned centerpiece of NASA's Mission to Planet Earth. Dozier's presentation outlined some of the recent changes in EOS. These included a total budget reduction of about 35%, from \$17B to \$11B, a change in implementation plans moving toward a greater number of smaller spacecraft rather than the previous concept of large platforms, and finally a reduction in instrumentation to be flown that reflects a narrowing in the scientific objectives. The first scientific priority will be on clouds, radiation, water vapor, and precipitation. Some of the EOS instruments are on planned flights and others are looking for flights of opportunity. One casualty of the budget reduction was the plan for EOS "hot spares", implying the possibility of data gaps in the event of instrument or spacecraft failure. Much of the EOS data will be obtained at very high spatial resolution, which will be valuable for studies of climate processes. The first EOS launch is planned for 1998.

**NOAA Monitoring.** L. Stowe (NOAA/NESDIS) presented NOAA's plans for monitoring the climate system. Improved versions of some of today's instruments will be flown. For instance, more channels are to be added to the AVHRR. Changes are also to be made in the infrared sounders and microwave sounders. In particular, the microwave sounding capability will be enhanced to measure more vertical levels and the water vapor profile. NOAA is also looking at some of the EOS instruments to possibly evolve into operational implementation.

**Solar Irradiance.** J. Lean (NRL) indicated that changes in the total solar irradiance and/or spectral irradiance can be of great importance to climate change. In light of this, she discussed the history of satellite measurements of total solar irradiance as well as solar spectral irradiance. She reminded us that recent satellite observations have clearly indicated the existence of both short and long time scale changes in total irradiance that are related to solar activity. The situation for spectral irradiance is different in that changes on short time scales are clear but changes on long time scales are not so well measured due to problems in calibration and continuity of measurement. Lean showed solar irradiance trends of the past decade measured by several instruments, emphasizing the differences in absolute irradiance among even the best calibrated instruments, implying the need for overlapping data from successive instruments if long-term trends are to be monitored. She emphasized that there are as yet no firm plans for long-term solar monitoring, despite the widely perceived potential importance of the sun in driving the earth's climate. Lean also stressed the important complementary role of ground-based solar observations.

**Tropospheric Aerosols.** Recently, a great deal of attention has been focused on the role of tropospheric aerosols in the context of climate changes. It has been suggested that while anthropogenic activities tend to lead toward global warming through enhancing the amount of CO<sub>2</sub> and other greenhouse gases, there is also the counterbalancing effect of producing more tropospheric aerosols through sulfur emissions. S. Schwartz (Brookhaven National Laboratories) proposed a network for monitoring aerosols concentrations and properties. Because of the spatial heterogeneity of aerosols, ground-based stations should be supplemented by satellite monitoring, but the satellite data will need to be much more accurate than current operational products if they are to be substantially useful.

*ARM.* G. Stokes (Pacific Northwest Laboratory) spoke about the planned Atmospheric Radiation Measurement (ARM) program that is being implemented by the U.S. Department of Energy (DOE). The ARM mission is aimed at improving our knowledge of radiative transfer and the role of clouds, with an emphasis on process studies. ARM includes measurements from ground-based facilities, remotely piloted aircraft, and satellites.

*ARMSat.* Finally, J. Vitko (Sandia National Laboratory) discussed DOE's planned ARMSat program. He indicated that DOE sees ARMSat as using DOE experience in space science and engineering to build small spacecraft that obtain measurements that are important for the understanding of clouds, radiation and climate changes.

In summary, those spacecraft and surface observations that are planned for the next several years will obtain very interesting data for the study of climate change. These planned programs do not mitigate the need for the long-term monitoring by the proposed Climsat program, however.



## PART II: PROPOSED CLIMSAT MISSION

### 7. Climsat Rationale

*James Hansen, NASA Goddard Institute for Space Studies*

A brief but comprehensive overview of the Climsat rationale is provided by the Executive and Workshop Summaries (pp. vii-xv). More detailed information is provided in the science papers (Sections 1-6) above and in the instrument and data sampling papers (Sections 8-12) below. Here we summarize reasons for the Climsat proposition, and cover some aspects not treated in the other sections. We also stress the need for certain climate monitoring other than that supplied by Climsat, especially solar irradiance, and we stress the complementarity of Climsat monitoring to plans for detailed EOS measurements.

Table 7.1 summarizes the fact that existing and planned observations will not provide measurements of most climate forcing and feedback parameters with the accuracy needed to measure plausible decadal changes. In this table a dash in the second column signifies the absence of calibrated data meeting the requirements in the mid 1990s. Stratospheric water vapor and aerosol requirements are not met, for example, even though the present SAGE II instrument on the ERBS spacecraft measures those two parameters accurately, because ERBS is not expected to last more than a few years and it does not provide global coverage. We stress the imminence of a potential data gap even of those parameters, such as solar irradiance and stratospheric aerosols, for which monitoring capability has been proven and currently is in place.

We find that most of the missing global climate forcings and feedbacks can be measured by three small instruments, which would need to be deployed on two spacecraft to obtain adequate sampling and global coverage. The monitoring must be maintained continuously for at least two decades. Such continuity can be attained by replacing a satellite after it fails, the functioning satellite providing calibration transfer to the new satellite. Certain complementary monitoring data are also needed, including solar monitoring from space, in order to fully meet requirements for monitoring all the climate forcings and feedbacks. The complementary data needs are discussed toward the end of this section.

We summarize the proposed Climsat measurements and compare the expected accuracies to those which are needed to analyze changes of the global thermal energy cycle on decadal time scales. We stress the need to get broader participation of the scientific community in the monitoring and analysis activity. Finally, we discuss related climate process and diagnostic measurements.

#### Climsat Measurements

Measurements by the three proposed Climsat instruments cover practically the entire thermal and solar spectra, as summarized in Fig. 7.1. This 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 which we already know about. All radiative forcings and feedbacks operate by altering the solar or thermal spectra in some way.

The Climsat instruments are designed to exploit the full information content in the emitted thermal and reflected solar spectra. In the thermal region information is contained primarily in the high resolution spectral variations of the radiance (Conrath *et al.*, 1970; Hanel *et al.*, 1972b; Kunde *et al.*, 1974; Clough *et al.*, 1989b). On the other hand, because incident sunlight is unidirectional, the 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).

MINT (Michelson Interferometer) covers the spectral range 6-40  $\mu\text{m}$ , the long wavelengths being important for defining the water vapor distribution. Its high spectral resolution and high

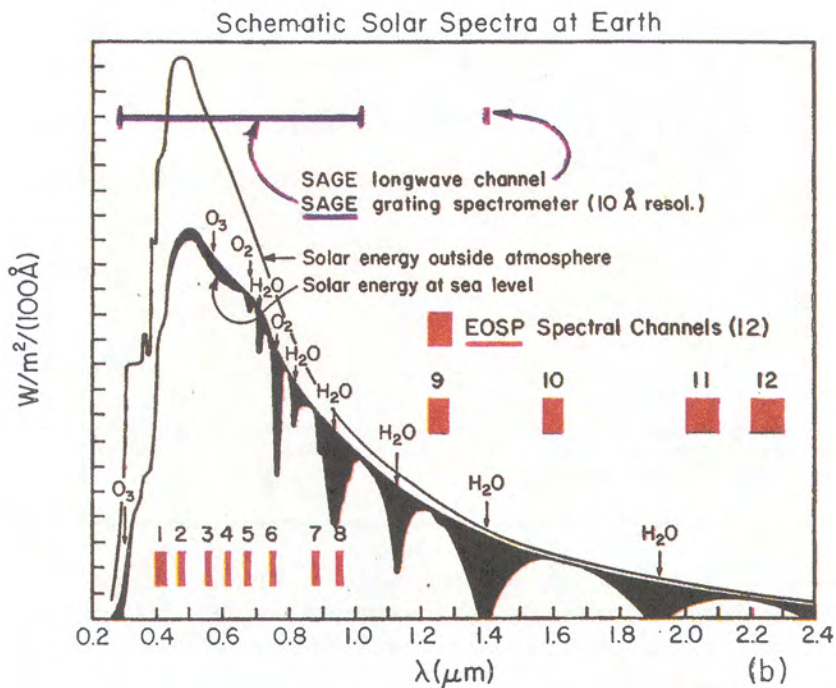
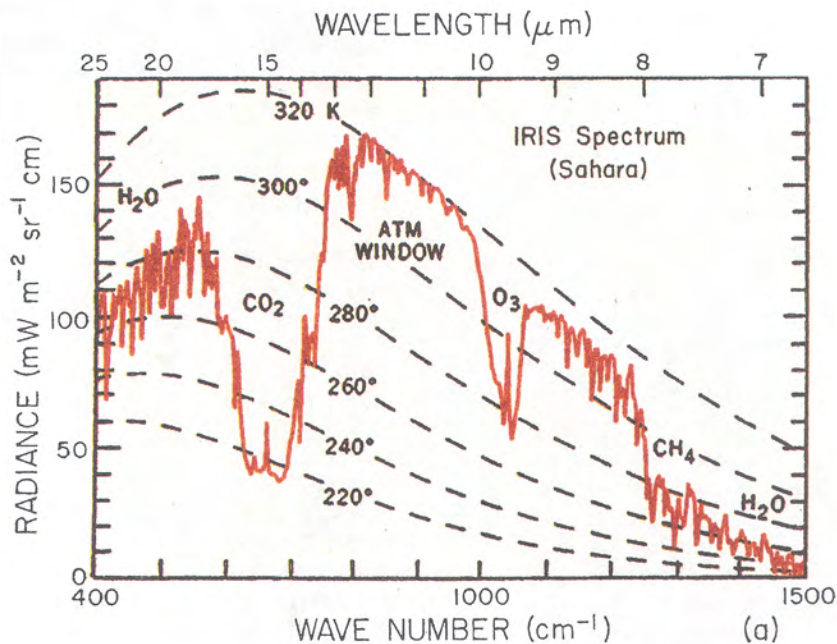
TABLE 7.1. Principal Global Climate Forcings, Radiative Feedbacks, and Diagnostics

	1996 Calibrated Source Meeting Requirements	Proposed ClimSat Contributions	Needed Complementary Data
<b>Climate Forcings</b>			
Greenhouse gases			
CO <sub>2</sub> , CFCs, CH <sub>4</sub> and N <sub>2</sub> O	G	—	—
O <sub>3</sub> (profile)	—	SAGE	NDSC
stratospheric H <sub>2</sub> O	—	SAGE	—
Aerosols			
tropospheric	—	EOSP (SAGE)	Surface reference network
stratospheric	—	SAGE (EOSP)	Surface reference network
Solar Irradiance	—	—	ACRIM, SOLSTICE
Surface Reflectivity	—	EOSP	—
<b>Radiative Feedbacks</b>			
Clouds			
cover	O	MINT/EOSP	—
height (temperature)	—	MINT/EOSP/SAGE	—
optical depth	—	MINT/EOSP	—
particle size	—	MINT/EOSP	—
water phase	—	MINT/EOSP	—
Lower tropospheric H <sub>2</sub> O (profile)	O, W	MINT	Reference radiosonde
Upper tropospheric H <sub>2</sub> O (profile)	—	SAGE/MINT	Reference radiosonde
Sea Ice Cover	O	—	—
Snow Cover	O	—	—
<b>Climate Diagnostics</b>			
Temperature			
upper air	W, O	MINT	Reference radiosonde
surface air	W	—	—
sea surface	S, O	MINT	—
Ocean			
internal temperature	—	—	Continuation of WOCE, acoustic tomography
surface salinity	—	—	Continuation of WOCE
transient tracers	—	—	Continuation of WOCE
Radiation Budget			
top of atmosphere	—	—	SCARAB, CERES
surface	—	—	WCRP Baseline Network

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. MINT = Michelson Interferometer.

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, as well as tropospheric water vapor, ozone and temperature.

EOSP (Earth Observing Scanning Polarimeter) covers the solar spectrum from the near ultraviolet (0.4  $\mu\text{m}$ ) to the near infrared (2.25  $\mu\text{m}$ ) 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, as well as an independent measurement of detailed cloud properties.



**Fig. 7.1.** (a) 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  $\text{cm}^{-1}$ , and higher resolution (2  $\text{cm}^{-1}$ ). (b) Location of the EOSP and SAGE III spectral channels, relative to a typical spectrum of solar radiation.

TABLE 7.2. Climsat Sensors

SAGE III	EOSP	MINT
Earth-limb scanning grating spectrometer, UV to near IR, 10 Angstrom resolution.	Cross-track and along-track scans of radiance and polarization, 12 bands near UV to near IR.	Michelson interferometer, 2 cm <sup>-1</sup> resolution from 6μm to 40μm; 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 <sub>3</sub> , H <sub>2</sub> O, NO <sub>2</sub> , NO <sub>3</sub> , OCIO - most down to cloud tops.	Yields aerosol optical depth, 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: 19 kg	Mass: 20 kg
Power (mean/peak): 10/45 W	Power (mean/peak): 15/22 W	Power (mean/peak): 14/22 W
Mean Data Rate: 0.45 Tbps*	Mean Data Rate: 1.6 Tbps*	Mean Data Rate: 0.7 Tbps*
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

\* Tbps = Terabits/year; Mission Comparison: ISCCP = 0.2 Tbps; CLIMSAT = 5 Tbps; EOS = 2500 Tbps [one Terabit is approximately 1000 tapes (6250 bpi) per year]

SAGE III (Stratospheric Aerosol and Gas Experiment III) observes the sun and moon through the Earth's atmosphere obtaining an extinction profile 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<sup>-3</sup> μm) from 0.29 μm to 1.02 μm. It also adds a detector at 1.55 μm. SAGE III will provide absolutely calibrated profiles of stratospheric aerosols, stratospheric water vapor, and ozone, extending and improving upon predecessor data.

Table 7.2 summarizes specific technical data on each of the three instruments, and Table 7.3 lists several characteristics which apply to the complement of the three instruments. All of these six characteristics are essential for Climsat to meet its scientific objectives while requiring only moderate resources.

Perhaps the most crucial characteristic of the Climsat instruments is that they are all self-calibrating to very 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 very high wavelength-to-wavelength precision. 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 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. Although it is not possible to precisely state instrument costs at this early stage of definition, two of the three instruments have gone through phase A/B studies in the EOS program, which produced government estimated costs of \$15M to \$20M per instrument for the first copy, and substantially lower costs for additional copies.

**TABLE 7.3. Climsat Instrument Characteristics**

- 
1. **Cover Solar and Thermal Spectra:** encompass surprises
  2. **Self-Calibrating:** yields the high precision required for monitoring small changes
  3. **Small:** fits on Pegasus-class launcher
  4. **Proven Technology:** space-tested heritage
  5. **Long-Life Capability:** predecessors all have demonstrated lifetimes > 10 years
  6. **Inexpensive**
- 

Figure 7.2a provides a size comparison of different spacecraft, showing that Climsat is very small in comparison to other familiar spacecraft. The small size and mass of Climsat allow it to fit on a Pegasus-class launcher (Fig. 7.2b). One advantage of this small size is that the cost of a Pegasus launch is only about \$10M.

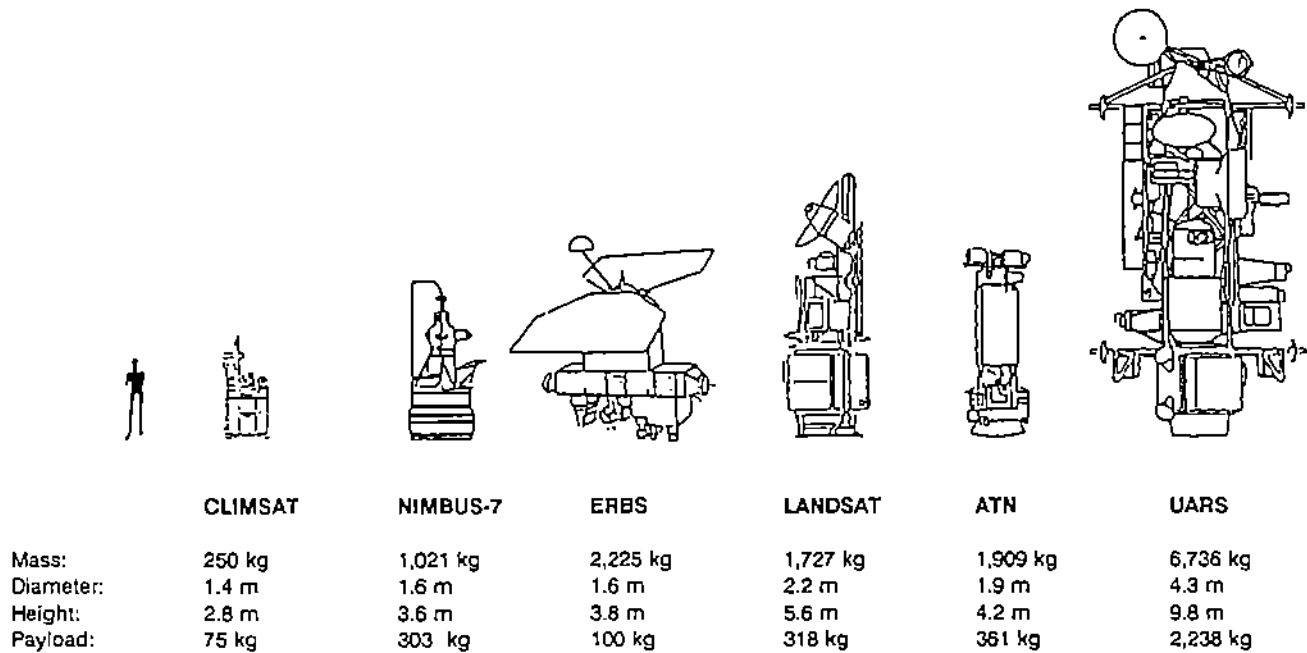
#### Measurement Accuracies

We consider two criteria for specifying the accuracies with which climate forcings and feedbacks need to be monitored. The first criterion is based on the plausible changes of the forcings and feedbacks during the next 20 years, as estimated in Section 3. At minimum, we would like a monitoring system capable of detecting such changes. The second criterion is the more demanding desire to determine quantitatively the contribution of every forcing and feedback to the planetary energy balance. We define a significant global mean flux change as  $0.25 \text{ W/m}^2$  or greater, based on the consideration that anticipated increases of greenhouse gases during the next 20 years will cause a forcing of about  $1 \text{ W/m}^2$ . The accuracy requirements resulting from these two criteria are listed in the second and third columns of Table 7.4.

The capabilities of the proposed Climsat mission depend on the instrumental accuracies and precisions, and also on the sampling provided by the Climsat orbits. The instrumental capabilities are discussed in Sections 8–10 and the sampling in Sections 11–12. Reliable determination of the ultimate capabilities is extremely difficult, and further simulations of instrument performance, data inversion techniques, and sampling studies will be 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 Climsat capabilities are given in the fourth column of Table 7.4 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 is clear that, in general, Climsat is 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  $0.25 \text{ W/m}^2$ , can also be achieved readily for all the climate forcings except aerosol induced cloud changes. This latter forcing can be measured in the regions of (measured) large aerosol changes, which may allow an inference of the corresponding global forcing. It appears that Climsat may be just marginally capable of measuring most of the feedbacks, mainly cloud parameter changes, to the  $0.25 \text{ W/m}^2$  criterion. Direct measurement of cloud optical thickness change to this accuracy does not appear to be achievable. The alternative of measuring the corresponding cloud albedo changes over decades is also just outside the capability which is proven for the EOSP calibration lamps on the basis of planetary flight experience. 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).

### Size Comparisons of Several Spacecraft



### Payload Weight (tons) to Low Earth Orbit

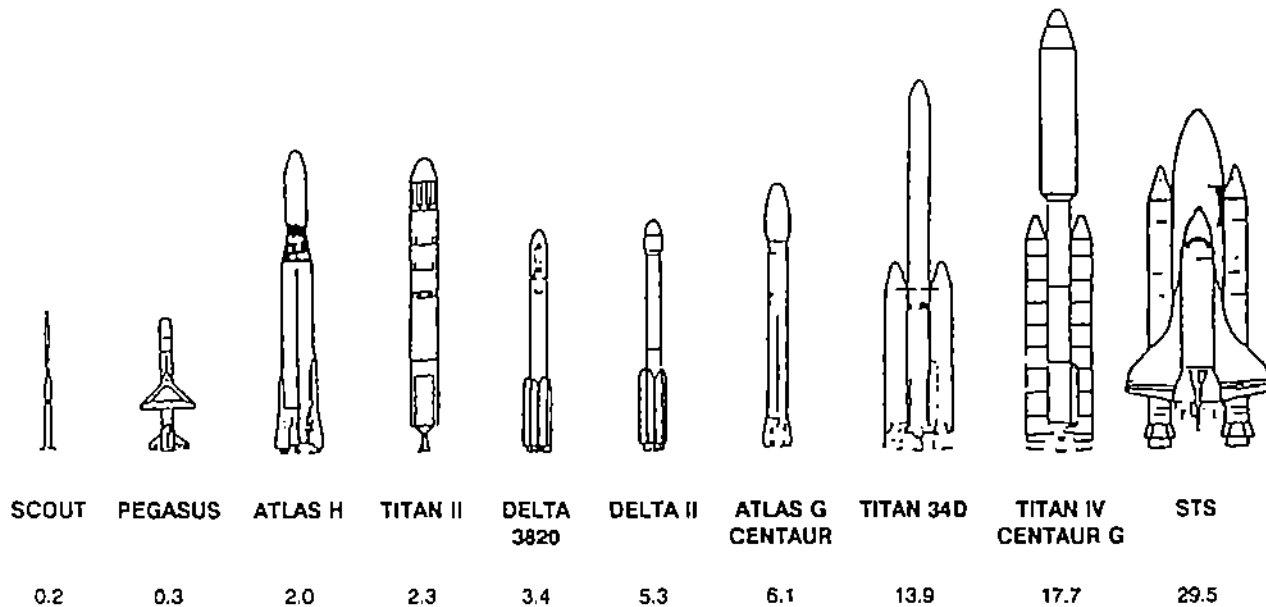


Fig. 7.2. (a) Size comparison of the proposed Climsat spacecraft with some familiar spacecraft. ATN is similar to polar orbiting meteorological spacecraft. (b) Payload comparison of different launchers; Climsat requires a Pegasus-class capability.

**TABLE 7.4. Comparison of estimated Climsat measurement accuracies with changes of forcing and feedback parameters anticipated on a 20 year time scan and with the parameter changes required to yield a flux change of  $0.25 \text{ W/m}^2$ .**

Forcing or Feedback	Plausible 20 Year Change	Global Change Required to Yield $\Delta \text{Flux} = 0.25 \text{ W/m}^2$	Climsat Accuracy Estimated for Regional/Seasonal Mean	Climsat Accuracy Estimated for Global Decadal Change
Ozone	Altitude and Height dependent	10% of $\text{O}_3$ at 15-20 km	10%	3%
Stratospheric $\text{H}_2\text{O}$	$\frac{\Delta q}{q} = 0.3$	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 $\text{H}_2\text{O}$ upper lower	$\frac{\Delta q}{q} = \begin{cases} .10 \\ .04 \end{cases}$	0.02 0.02	0.05 0.03	0.03 0.02
Cloud cover cirrus stratus	$\Delta C = \begin{cases} 0.03 \text{ (regional)} \\ 0.03 \text{ (regional)} \end{cases}$	0.004 0.003	0.02 0.02	0.004 0.004
Cloud Top temperature pressure	$\Delta T = 1 \text{ K}$ $\Delta p = 12 \text{ mb}$	0.4 K 5 mb	1 K 15 mb	0.3 K 5 mb
Cloud Optical Depth cirrus stratus	$\Delta \tau = \begin{cases} 0.1 \\ 1 \end{cases}$	0.02 0.07	0.1 0.5	0.05 0.2
Cloud Particle Size (water)	$\Delta r = 1 \mu\text{m}$	0.2 $\mu\text{m}$	0.5 $\mu\text{m}$	0.2 $\mu\text{m}$

In summary, Climsat would be capable of detecting plausible decadal changes of those climate forcings and feedbacks which it addresses. In most cases, if not all, Climsat can quantify the forcings to the high precision ( $0.25 \text{ W/m}^2$ ) desired to help interpret global climate change. Climsat is also close to achieving that level of precision for the climate feedbacks. Thus the feedback measurements should be of great value as a complement to the usual approach of analyzing feedbacks, which consists of a combination of modeling and process observations, the latter being used to improve the models iteratively.

### Complementary Monitoring Requirements

Although Climsat can provide many of the missing climate forcings and feedbacks with the required accuracies, certain other monitoring is needed to complete the full set of data requirements. Complementary long-term monitoring requirements are summarized in the final column of Table 7.1.

The most crucial requirement is for long-term monitoring of the sun. The sun provides the ultimate drive for the Earth's climate, including the global thermal energy cycle. 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 require solar changes of as little as several tenths of a percent (Wigley, 1988; Wigley and Kelley, 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 percent over the last 11 year solar cycle. It is essential 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 (Fig. 2.8; Lean, 1991). The UARS mission (Reber, 1990) includes ACRIM II, which precisely monitors total solar irradiance, but it is very important to make immediate plans for prompt flight of another ACRIM or its equivalent.

It is also necessary 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 urgently needed. Total and spectral irradiance monitors would both appear to be prime candidates for flight on small satellites.

Several of the parameters which Climsat 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. Although SAGE III will be more capable than predecessor instruments in this regard, 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 the Climsat mission is implemented, monitoring of the ozone profile should be adequate for the purpose of defining ozone climate forcing.

Similarly, monitoring of tropospheric aerosols from space with the required high precision is new. It will be important to have detailed aerosol "ground truth" monitoring and periods of special detailed study at a number of continental and marine stations, as is being discussed (Charlson, Schwartz, private communication). Finally, monitoring of upper tropospheric water vapor from space needs to be supplemented by improved radiosonde measurements, which requires introduction of instruments with improved accuracy and calibration (Gaffen *et al.*, 1991).

### Community Involvement

Success of such a climate monitoring system can be attained only if there is broad involvement of the scientific community. Rapid production and broad availability of the data products is an essential requirement. For the data to be fully effective, it also will be crucial to provide resources to the scientific community, through an announcement of opportunity process, to carry out studies with the data. Representatives of the community must be involved in the design of the monitoring system at the earliest stages. Thus if a Climsat project is approved for further development, there should be a Dear Colleague letter or Announcement of Opportunity to solicit involvement of representative members of the community in the further definition and implementation of the mission.



It is recognized that relevant scientific and engineering expertise are distributed in the private sector, universities and the government. Thus one effective way to initiate a satellite mission may be via consortia responding to a request for small satellite proposals. A proposal selected through this mechanism could potentially reduce procurement delays. This is particularly important, because only if the project development time is minimal, say four years or less, will it be possible to fill the impending data gaps for key climate parameters. The prospect of prompt results is also important for attracting the best scientists to participate.

#### **Relation to Climate Process and Diagnostic Studies**

Long-term monitoring of global climate forcings and radiative feedbacks is, of course, only a portion of global climate measurements (cf., USGCRP, 1993). There is a great 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 feedbacks together with improved understanding and modeling of climate processes is required to obtain predictive capability of 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. Also, 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 must be complemented by a continuing series of altimetry and scatterometer space missions 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. A recent proposal to fly the CERES instrument on a small satellite in formation with a NOAA polar orbiting meteorological satellite would provide an improved ability to study the relation of clouds and the earth's radiation budget. In addition, much more detailed studies should be possible with the EOS mission, since 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 of 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 1998 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 will be more valuable if they are 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 fluxes.

**TABLE 7.5. Why equivalent monitoring data cannot be obtained from EOS.**

1. EOS does not include all of the Climsat instruments or an adequate equivalent. EOSP is not confirmed for flight, but may fly on the second AM polar platform. SAGE is not confirmed for flight, but may be flown on its own satellite in an inclined orbit. The very high wavelength-to-wavelength precision of the Michelson Interferometer using a single, passively cooled detector without scanning is crucial for obtaining the required accuracy. AIRS on EOS uses separate detectors for each wavelength, requiring individual calibrations, is actively cooled and does not cover the thermal spectrum.
2. Proposed EOS flights of EOSP and SAGE and the flight of AIRS do not provide the required sampling and coverage, since only one copy of each instrument is flown in a single orbit. Instruments on the polar orbiter provide a diurnally biased global coverage. SAGE in an inclined orbit does not provide coverage of the polar regions.
3. The monitoring datasets must be contemporaneous, continuous and long-term (several decades), since the climate system integrates the forcings. Current EOS plans do not insure contemporaneous flights of these instruments, the lack of "hot spares" will probably preclude continuity. If one of these small instruments failed on an EOS platform, would the whole platform be replaced?
4. It is not economical to add the Climsat instruments to a large satellite. Flight of a few small instruments is better suited to a small satellite and avoids "all eggs in one basket".
5. A two satellite system with identical instruments can guarantee overlapping observations for cross-calibration if satellites that fail are replaced promptly, which is critical for long-term data precision. EOS plans do not include such cross-calibration.
6. It is realistic to maintain the low cost, small Climsat system over several decades. Continuous monitoring with EOS is prohibitively costly.
7. Even if all the Climsat instruments were added to the EOS platforms, they would be unlikely to command the priority essential to success (regarding launch dates when there are funding shortfalls, mission operations when there are power or other constraints, etc.)

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#### **Complementarity to EOS**

We anticipate that the acquisition of high precision time series of climate forcings and radiative feedbacks will increase the demand for detailed measurements of climate processes. The forcing and feedback data would thus play a role in study of the thermal energy cycle somewhat analogous to that which Keeling's CO<sub>2</sub> monitoring played for study of the carbon cycle. EOS, by providing high resolution detailed observations, should be nicely complementary to Climsat monitoring.

The question naturally arises as to whether the climate forcing and feedback information could not be extracted from the EOS observations. The reasons that this is not the case are summarized in Table 7.5. All of the Climsat instruments or their equivalents are not included on EOS, and those which are do not have the orbits and sampling required to yield the necessary precision of the forcings and feedbacks. In particular the precessing inclined orbiter is critical to the elimination of diurnal measurement bias. The absence of "hot spares" for the EOS spacecraft makes continuity of the data unlikely, a crucial drawback for climate forcing time series. Also the two satellite Climsat approach is needed for instrument cross-calibration, which is critical to the long-term data precision.

It should also be noted that, if Climsat should be approved for implementation, it would relieve EOS of certain burdens, such as the need for a SAGE inclined orbiter and EOSP on the AM-2 platform. These savings could help keep the EOS budget within congressionally imposed constraints and free resources for other purposes, assuming that Climsat were funded outside the EOS budget.

## 8. Stratospheric Aerosol and Gas Experiment (SAGE III)

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Aerosols, ozone, and water vapor are among the most important global radiative forcings and feedbacks. Volcanic aerosols in the stratosphere can cool the climate significantly, especially after exceptional eruptions such as that of Mt. Pinatubo (Lamb, 1970; Toon and Pollack, 1980; Self and Rampino, 1988; Robock, 1991; Hansen *et al.*, 1992). Reductions in lower stratospheric ozone may have had a cooling effect during the last decade (Lacis *et al.*, 1990; Ramaswamy *et al.*, 1992; Hansen *et al.*, 1993). Tropospheric water vapor may increase in a warming climate, providing a positive feedback (Hansen *et al.*, 1984; Schlesinger and Mitchell, 1987; IPCC, 1990, 1992), but the magnitude of this feedback is sensitive to changes in water vapor in the upper troposphere which depend on poorly understood convective processes (Arking, 1993). In addition, it has been estimated that a doubling of stratospheric water vapor could lead to a 1°C global average warming of the surface (Wang *et al.*, 1976).

The proposed SAGE III instrument would be the principal source of data for global changes of stratospheric aerosols, stratospheric water vapor and ozone profiles, and a contributing source of data for upper tropospheric water vapor, aerosols and clouds (Table 8.1). The ability to obtain such data has been demonstrated by the predecessor instrument, SAGE II, but SAGE III will be substantially more capable, as discussed below. The capabilities for monitoring the profiles of atmospheric constituents have been verified in detail, including ground-based validations, for aerosols (Osborn *et al.*, 1989), ozone (Cunnold *et al.*, 1989a) and water vapor (Rind *et al.*, 1993). Indeed, because of its self-calibrating characteristics, SAGE II was an essential component of the international ozone trend assessments (Watson *et al.*, 1988), and SAGE II is now proving to be invaluable in tracking the aerosols from Mt. Pinatubo. Although SAGE profiles generally terminate at the height of the first tropospheric cloud layer, it has been found that the measurements extend down to 3 km altitude more than 40 percent of the time at most latitudes (Rind *et al.*, 1993). Thus, useful information can also be obtained on upper tropospheric aerosols, water vapor and ozone.

**TABLE 8.1. SAGE III measurement objectives, instrument characteristics and key advantages.**

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### Measurement Objectives

Principal source of data for global change of: stratospheric aerosols, stratospheric water vapor, and ozone profile.  
 Contributing source of data for upper tropospheric water vapor, aerosols, cloud tops, and temperature profiles.  
 Other parameters important to atmospheric chemistry and physics, e.g., NO<sub>2</sub>, NO<sub>3</sub>, ClO abundances and polar stratospheric clouds (PSCs).

### Instrument Characteristics

Observes sun (and the moon, with SAGE III) during occultation by the Earth's limb.  
 Instantaneous field of view of 0.5 km, yielding high vertical resolution along the tangent path.  
 Grating spectrometer and linear CCD detector array yielding 1 nm (10<sup>-3</sup> μm) spectral resolution from 0.29 to 1.02 to μm, with additional channel at 1.55 μm.  
 Self-calibrating to high precision, based on viewing sun (or moon) just seconds before or after occultation.

### Key Advantages

High precision data for key climate forcings and feedbacks especially stratospheric and upper tropospheric aerosols, water vapor and ozone.  
 Extends important ongoing time series of these climate parameters.  
 SAGE III provides substantial improvements in spectral range, measured quantities and sensitivity compared to predecessor instruments.

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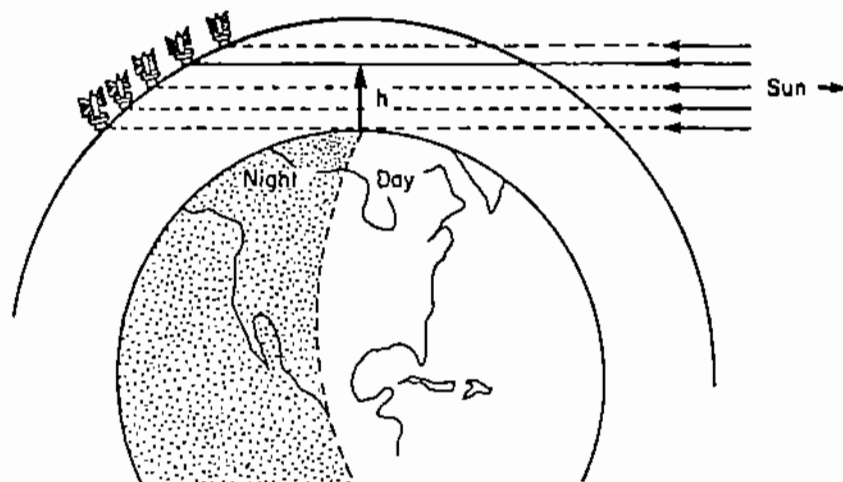


Fig. 8.1. Occultation geometry of spacecraft-earth-sun. The instrument views the sun during both sunrise and sunset as the sunlight passes through various depths of the earth's atmosphere, comparing the solar spectrum to that obtained by observing the sun above the atmosphere.

SAGE III and its predecessors are solar occultation instruments, that is, they measure the extinction of sunlight as the sun passes behind the earth's atmosphere as viewed from the spacecraft (Fig. 8.1). Because the sun is a strong source of energy, a small field-of-view can be used, typically 0.5 arc min, which corresponds to a height increment of only 0.5 km in the earth's atmosphere. The horizontal resolution across the earth's limb is about 200 km.

One advantage of occultation measurements is the simple relationship between the amount of adsorbing or scattering material and the magnitude of extinction of the transmitted radiation. But perhaps most important is the natural self-calibration that occurs before or after every measurement as the sun is viewed above the atmosphere; this greatly reduces the effect of potential changes of instrument transmission or detector sensitivity, allowing accurate measurement of even very small changes over long periods. However, even with the advantage of self calibration, it is important to document any instrument-to-instrument differences, and such capability is provided by the proposed two-satellite Climsat system.

SAGE III has a heritage of four instruments, listed in Table 8.2, none of which ever experience a failure in orbit. Indeed, SAM II and SAGE II continue to function today, although the Nimbus-7 spacecraft carrying SAM II is degrading. Each successive SAGE instrument has added new spectral channels while retaining the earlier channels. This allows the oldest data series to be continued, while initiating new monitoring of additional atmospheric constituents. Special care is required to minimize impacts of instrument-to-instrument change; for example, systematic differences appear to exist in the ozone profiles derived from SAGE I and SAGE II (Stolarski *et al.*,

TABLE 8.2. SAGE III predecessor instruments.

<u>Instrument (Spacecraft)</u>	<u>Operation Period</u>	<u>Spectral bands</u>	<u>Mass</u>
SAM (Apollo)	1975 (4 orbits)	1.0 $\mu\text{m}$	2 kg
SAM II (Nimbus-7)	Oct 1978 - present	1.0 $\mu\text{m}$	17 kg
SAGE I (AEM 2)	Feb 1979 - Nov 1981	0.385, 0.45, 0.6, 1.0 $\mu\text{m}$	30 kg
SAGE II (ERBS)	Oct 1984 - present	0.385, 0.448, 0.453, 0.525, 0.6, 0.94, 1.02 $\mu\text{m}$	30 kg

1991). The high spectral resolution of SAGE III, and the overlapping coverage of a two-satellite system, should minimize if not eliminate that problem.

The relationship between spectral occultation measurements and atmospheric extinction is illustrated in Fig. 8.2, which shows the sources of atmospheric extinction at 18 km altitude. The SAGE III predecessor instruments each used only a few specific channels within the indicated spectral range. However, SAGE III will take full advantage of the grating spectrometer which disperses the solar spectrum in all the SAGE instruments: SAGE III will use as its detector a CCD linear array covering the 290-1020 nm region with 1 nm resolution. This spectral resolution across absorption features of different gases will make retrievals of their abundance profiles significantly more accurate than for the predecessor instruments (Mount *et al.*, 1987). Extension of the wavelength coverage to 290 nm will allow O<sub>3</sub> measurements up to 85 km altitude. Data from several wavelengths at and near the oxygen 760 nm absorption band will yield a direct determination of temperature and density profiles, thus enabling the SAGE III retrievals to be independent of external data products. SAGE III will also include an isolated channel at 1550 nm; the increased wavelength coverage will provide valuable information on the aerosol size distribution, which is needed to accurately define the aerosol climate forcing (Lacis *et al.*, 1992).

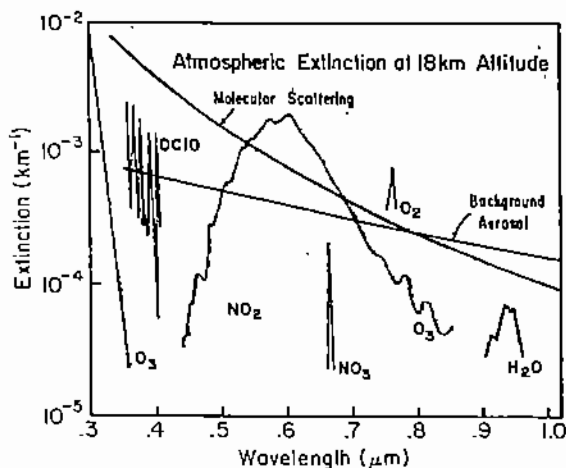


Fig. 8.2. Extinction contributions from different atmospheric constituents at 18 km altitude. On SAGE III a CCD linear array will provide 1 nm resolution from 0.29μm to 1.02μm, with an additional channel at 1.55μm.

The important improvements of SAGE III over its predecessors are summarized in Table 8.3. Observation of lunar occultations, as well as solar occultations, will increase the global sampling and include nighttime data. The use of 16-bit accuracy in A-D conversion will decrease the quantization error and increase the dynamic range of the data. Overall, the improved spectral resolution, increased

TABLE 8.3. SAGE III design improvements over SAGE II, and expected science benefits.

Addition	Improvement	Science Benefit
CCD	Increased wavelength discrimination (1-2 nm)	Differential absorption for H <sub>2</sub> O, NO <sub>2</sub> , O <sub>3</sub> , OCIO, & NO <sub>3</sub> Solar Fraunhofer spectra calibration Variable integration time Increased aerosol characterization Independence from external data
Lunar Occultation	Nighttime measurement	NO <sub>3</sub> and OCIO key to O <sub>3</sub> chemistry Expanded geographic coverage
290 nm Channel	Short wavelength measurement	O <sub>3</sub> measurement through the mesosphere
1550 nm Channel	Long wavelength measurement	Better aerosol & cloud characterization Extended measurement into lower troposphere
16-Bit AD	Decreased quantization error Increased dynamic range	Improved accuracy & altitude measuring range

spectral coverage, and higher sensitivity of SAGE III will increase the accuracy of the aerosol, ozone and water vapor data, and extend the measurements deeper into the troposphere.

The single profile measurement accuracies of SAGE III are estimated in Table 8.4, on the basis of simulations using SAGE III design parameters as well as experience from SAM II, SAGE I and SAGE II validation programs. The validation included comparison of satellite profile retrievals with lidar and radiosonde measurements (Cunnold *et al.*, 1989a,b; Osborn *et al.*, 1989; Rind *et al.*, 1993).

The sparse density of occultation profiles is perhaps the greatest limitation of the data, the two solar occultations per orbit providing about 750 profiles per month. This sampling is increased about 50 percent by the lunar occultations of SAGE III. The internal variability of the existing data suggest that the SAGE sampling can provide accurate zonal mean seasonal mean stratospheric profiles. However, the quantitative numerical sampling studies discussed below should be extended to assess the potential of the SAGE measurements for tropospheric monitoring, particularly when complemented by measurements from EOSP and MINT.

**TABLE 8.4. SAGE III measurement capabilities for a single profile, based on simulations using SAGE III design parameters and experience gained in validating most of these species with SAM II, SAGE I and SAGE II "ground-truth" programs.**

Parameters Measured In Occultation	Spectral Range ( $\mu\text{m}$ ) Profiles produced at these $\lambda$ 's	Alt. Range (km)	Vert. Resol. (km)	Single Profile Retrieval Estimated Accuracy (Random Component)	
				%	Vertical Range (km)
<b>SOLAR</b>					
Aerosols, Cloud tops, and PSC's	0.385, 0.440, 0.525, 0.760, 0.930, 1.020, 1.550	0-40	1	5	10-25
Ozone	0.290 and 0.600	6-85	1	5	10-50
H <sub>2</sub> O	0.920-0.960	3-50	1	10	5-40
NO <sub>2</sub>	0.430-0.450	10-50	1	10	15-40
O <sub>2</sub> and Temp.	0.740-0.780	6-70	1	2 2K	6-60 6-60
<b>LUNAR</b>					
Aerosols, Cloud tops, and PSC's	0.385, 0.440, 0.480, 0.525, 0.760, 0.930	0-40	1	5	10-25
Ozone	0.470-0.490	15-40	1	5	15-40
H <sub>2</sub> O	0.920-0.960	3-50	1	15	6-25
NO <sub>2</sub>	0.430-0.450	20-50	1	10	20-40
NO <sub>3</sub>	0.640-0.680	20-55	1	10	35-50
OCIO	0.380-0.420	15-25	3	25	At [OCIO] peak during "disturbed" conditions
O <sub>2</sub> and Temp.	0.740-0.780	6-55	1	2 2K	10-40 10-40

## 9. Earth Observing Scanning Polarimeter

Larry Travis, NASA Goddard Institute for Space Studies

Climate forcing by tropospheric aerosols, discussed briefly above (Section 3), is receiving increased attention because of the realization that the climate effects may be large, while our knowledge of global aerosol characteristics and temporal changes is very poor. Tropospheric aerosols cause a direct radiative forcing due simply to their scattering and absorption of solar radiation, as well as an indirect effect as cloud condensation nuclei which can modify the shortwave reflectivity of clouds. Sulfate aerosols tend to increase planetary albedo through both the direct and indirect effects; Charlson *et al.* (1992) estimate a cooling due to anthropogenic sulfate aerosols of order  $1 \text{ W/m}^2$ , noting that this is similar in magnitude to the present anthropogenic greenhouse gas warming. Other aerosols, including those from biomass burning (Penner *et al.*, 1992) and wind-blown desert dust (Tanre *et al.*, 1988; Joseph, 1984; Coakley and Cess, 1985) are also of potential climatic importance.

At present, the only global monitoring of tropospheric aerosols is a NOAA operational product, aerosol optical thickness, obtained using channel-1 ( $0.58\text{--}0.68 \mu\text{m}$ ) radiances from the AVHRR (Rao *et al.*, 1988). With this single channel radiance data, one must use an approach which is based on the inferred excess of reflected radiance owing to scattering by the aerosols over that expected from theoretical calculations. This approach is suited only for situations where the surface has a low albedo that is well known *a priori*. Thus, the NOAA operational product is restricted to coverage over the ocean at AVHRR scan angles well away from sun glint, and aerosol changes are subject to confusion with changes caused by either optically thin or subpixel clouds. Because optically thin aerosols have only a small effect on the radiance, accurate measurements for optical thickness less than 0.1 (which is a typical background level) are precluded. Moreover, some of the largest and most important aerosol changes are expected over land.

**TABLE 9.1. EOSP measurement objectives, instrument characteristics and key advantages.**

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### Measurement Objectives

Global distribution and nature of tropospheric aerosols: optical thickness, particle size and refractive index

Global cloud climatology: optical thickness, cloud-top pressure, particle size, particle liquid/ice phase

Global surface reflectance and polarization

Measurement precision needed to determine interannual and decadal changes of these parameters

### Instrument Characteristics

Scans limb to limb perpendicular to or along satellite ground track

Instantaneous field of view of 8 km (at nadir) with 180 samples per scan

Simultaneous radiance and polarization data for 12 bands between 410 and 2250 nm

High precision in-flight calibration with proven long-term stability

Polarization accuracy: 0.2% absolute; precision better than 0.1%

Radiometric accuracy: 5% absolute; decadal precision better than 2%

### Key Advantages

High sensitivity to aerosol properties, unattainable with only radiance measurements

Cloud properties more precise than obtainable with existing and planned meteorological satellites; includes detection and measurement of thin clouds, e.g., sub-visible cirrus; high sensitivity to cloud particle shape

Surface reflectance monitored to precision required to quantify decadal change

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TABLE 9.2. EOSP predecessor instruments.

Instrument (Spacecraft)	Operation Period	Spectral Bands	Mass
IPP (Pioneer 10)	Mar 1972 - present	0.45, 0.66 $\mu\text{m}$	4 kg
IPP (Pioneer 11)	Apr 1973 - present	0.45, 0.66 $\mu\text{m}$	4 kg
OCPP (Pioneer Venus)	May 1978 - Dec 1992	0.27, 0.37, 0.55, 0.94 $\mu\text{m}$	5 kg
PPR (Galileo)	Oct 1989 - present	0.41, 0.68, 0.94 $\mu\text{m}$	6 kg

Remote sensing of aerosols on other planets is more advanced than for the Earth, because the planetary measurements have made use of the significant additional information contained in the polarization of reflected sunlight. The effectiveness of polarimetry as a remote sensing tool was first convincingly demonstrated by analyses of ground-based observations of Venus (Hansen and Arking, 1971; Hansen and Hovenier, 1974), which were able to deduce basic microphysical and optical properties of the Venus clouds. Since then, spacecraft observations from polarimeters on the Pioneer 10 and 11 missions have provided information about aerosols on Jupiter (Smith and Tomasko, 1984), Saturn (Tomasko and Doose, 1984), and Titan (Tomasko and Smith, 1982) and on Venus from the Pioneer Venus Orbiter mission (Kawabata *et al.*, 1980).

The Earth Observing Scanning Polarimeter (EOSP) instrument, based upon design heritage and analysis techniques developed for planetary missions, will retrieve tropospheric aerosol characteristics from measurements of multispectral radiance and polarization. Moreover, the same radiance and polarization measurements will also provide very precise information on cloud properties and maps of surface characteristics for cloud-free regions. These capabilities also give EOSP the unique ability to discriminate aerosol from clouds and surface. Table 9.1 summarizes the EOSP objectives, characteristics, and advantages. As indicated in Table 9.2, the EOSP predecessor polarimeters on several planetary missions have demonstrated impressive lifetimes (OCPP operations ended after more than 14 years when the spacecraft entered the Venus atmosphere).

EOSP is designed to scan its 12-mrad IFOV from limb to limb through nadir, acquiring approximately 180 measurements of radiance and polarization in each of 12 spectral bands over each scan. The instrument may be oriented on the spacecraft so that it either scans perpendicular to the satellite ground track, thus obtaining global maps at about 10 km resolution (8 km IFOV footprint at nadir); or scans along the ground track, thus providing the capability of viewing a given location from a continuous range of zenith and phase angles as the spacecraft passes overhead. The EOSP on the inclined orbit Climatsat spacecraft will employ cross-track scanning, while the polar-orbiting spacecraft will employ along-track scanning. Thus the polar-orbiter will provide rapid scattering angle variation for a given region, optimizing information on aerosol characteristics, while the inclined orbiter provides daily (nearly) global coverage.

The approximate locations of the 12 EOSP spectral bands are illustrated in Fig. 9.1, along with a schematic solar spectrum for reference. These bands cover a wavelength range of a factor of six, which pro-

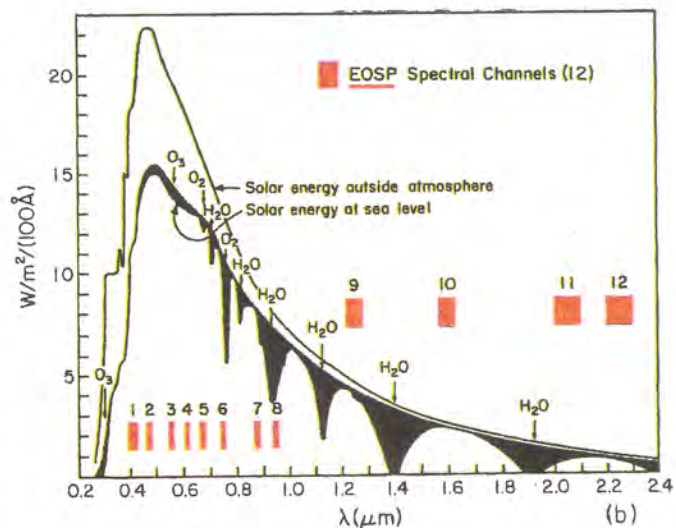


Fig. 9.1. EOSP spectral channels.



vides tremendous leverage for inference of aerosol and cloud particle physical properties (Hansen and Travis, 1974; Coffeen and Hansen, 1972). It is expected that the exact locations of the 12 EOSP bands would be specified during phase B instrument definition, after full science teams are selected for EOSP and ClimSat. Bands 1 and 8 (Fig. 9.1) are chosen to be near the extremes of the photodiode detector used for short wavelengths, and a second ultraviolet band (band 2) is located for the purpose of measuring cloud and aerosol altitude from the amount of Rayleigh scattering. The locations of the other five short wavelength bands (3 through 7) still could be adjusted. Similarly, the approximate locations of bands 9 and 12 are chosen to be near the extremes of the infrared detector, but bands 10 and 11 could be adjusted. Because of the high long-term precision of EOSP radiances, if bands are selected appropriately, the results may have a secondary benefit by providing a useful monitoring of surface, vegetation and ocean color properties on decadal time scales, in addition to the basic aerosol and cloud objectives.

The potential for aerosol retrieval is illustrated in Fig. 9.2, which summarizes the analysis of ground-based polarimetry of Venus. Observations at three different wavelengths show how multispectral coverage can be exploited to provide separate sensitivity to various characteristics. At  $0.365 \mu\text{m}$  (panel A), the relatively high contribution from Rayleigh (gas) scattering at middle phase angles provides an 'optical barometer', showing that the cloud tops are at a pressure level of about 50 mb. In panel B, we see that polarization at  $0.55 \mu\text{m}$  was able to constrain particle size with a sensitivity that probably excels that obtainable with many in situ particle size spectrometers. For Venus, the polarimetry at near-infrared wavelengths (panel C) provided a precise determination of the aerosol refractive index, which was the key information identifying the clouds as sulfuric acid.

Retrieval of aerosol properties from planetary polarimetry such as that illustrated in Fig. 9.2 has always employed trial-and-error fitting of the observations by multiple scattering computations for various cloud-aerosol models. Trial-and-error modeling is inappropriate for the routine generation of climate monitoring data products from EOSP. Instead, because of the complex behavior of the polarization, the inversion algorithms will be based on comparing observations with a large number of pre-computed models with parameter ranges spanning those from in situ aerosol measurements. Implementation will entail a decision tree process with tests based on appropriately developed thresholds, ratios, and differences for the multispectral radiance and polarization. With this table look-up approach, the computational requirements for operational processing will be modest; use of large database searches also exploits the very large memory and fast data storage properties of modern computers. The algorithm development and table generation computational effort are well within even present facility resources.

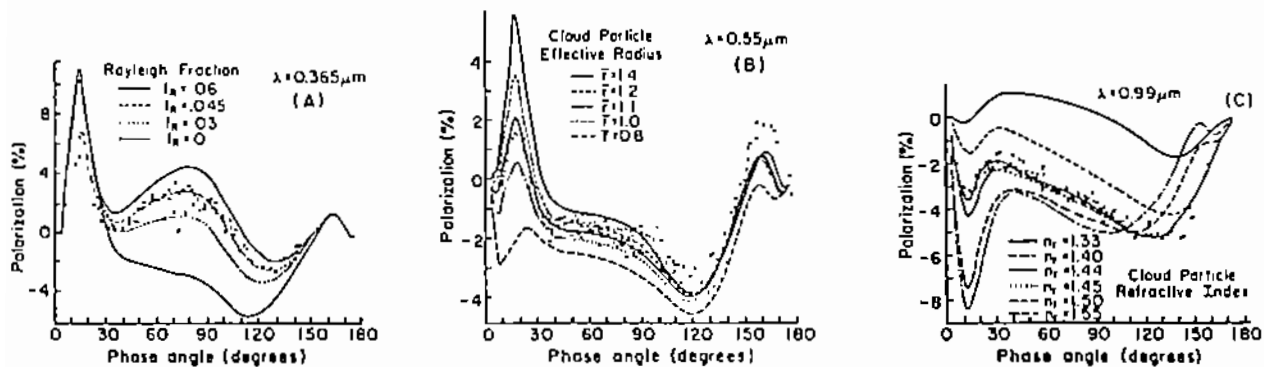


Fig. 9.2. Ground-based polarization studies of Venus clouds.

Aerosol retrieval must distinguish the relative contributions of the atmosphere and the surface. Over the ocean, the surface reflectivity is low (except in the sun glint region) and relatively predictable, so difficulties in extracting aerosol and cloud properties owing to the contribution of the surface to the observed radiance and polarization are minimized. The more interesting and challenging case is over land, where the surface reflectivity and polarization characteristics may be quite variable and are not well known *a priori*. Field measurements of the polarization of the scattered sunlight from vegetation indicate that, to first order, the polarized component arises from light specularly reflected at the leaf surface (Vanderbilt *et al.*, 1985). Because the specular reflection can be determined from the Fresnel equations, given the refractive index of the leaf, a simulation of the expected surface reflectivity and polarization for vegetation is possible since typical spectral properties of plants are adequately known. Such a simulation can demonstrate the ability of EOSP observations to discriminate aerosol and surface effects.

Simulation of the radiance and polarization for sunlight scattered by aerosols is straightforward using results from many in situ sampling and ground-based remote sensing studies to provide typical ranges of specific aerosol properties. The dominant aerosol component from the perspective of radiative influence globally is the sulfate aerosol generated over land from both natural and anthropogenic SO<sub>2</sub> emissions over land and dimethylsulphide emission from phytoplankton in the ocean (Charlson *et al.*, 1991). The mean particle size for this sulfate aerosol component is typically of order 0.1 to 0.3  $\mu\text{m}$ , and these particles are often more than 50 percent H<sub>2</sub>O at the relative humidities typical of the lower troposphere. Larger sized aerosol components are usually due to windblown dust and sea salt. Another aerosol component of increasing importance is smoke from biomass burning, whose typical size distribution is similar to that of the sulfate aerosol (Penner *et al.*, 1992). With the exception of dust, the major tropospheric aerosol components are hygroscopic, so these particles are liquid solutions and hence spherical. As a consequence, Mie scattering computations using the particle optical properties appropriate for the particular aerosol source provide an accurate specification of the single scattering characteristics for the aerosol. As for the irregularly shaped dust particles, there are now techniques (cf., Mishchenko, 1991a,b) which can treat scattering for non-spherical particles without resorting to modified Mie scattering approximations.

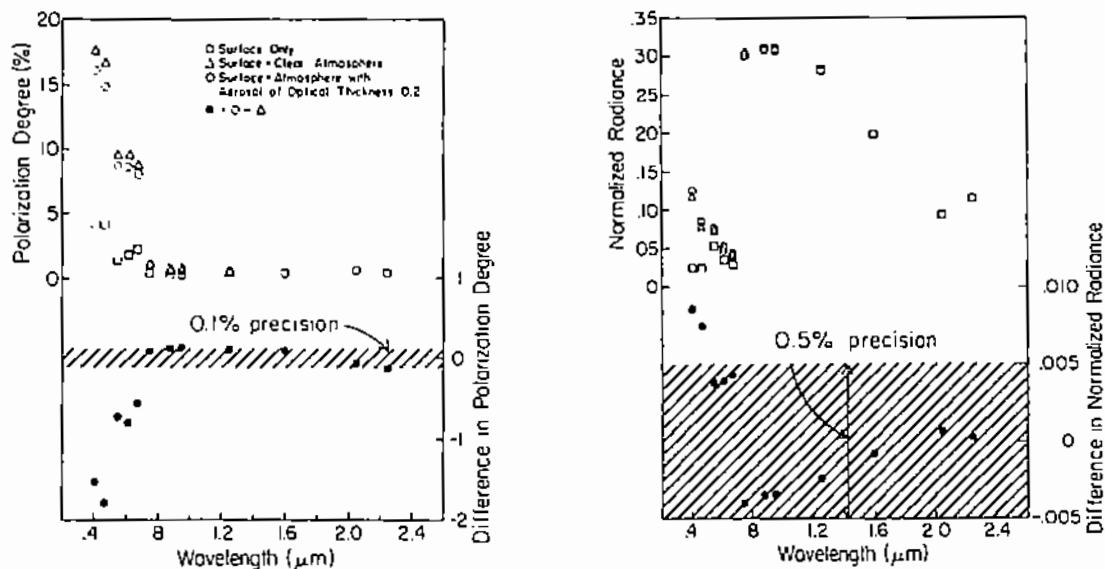


Fig. 9.3. Simulated polarization (left panel) and normalized radiance (right panel) for aerosol of optical thickness 0.2 over a land-vegetation surface. The cumulative contributions of surface, atmosphere (Rayleigh scattering) and aerosol are indicated by the open squares, triangles and circles, respectively for each EOSP spectral band. Filled circles in the bottom portion of each panel show the differences in polarization and normalized radiance between the aerosol and clear atmosphere cases.

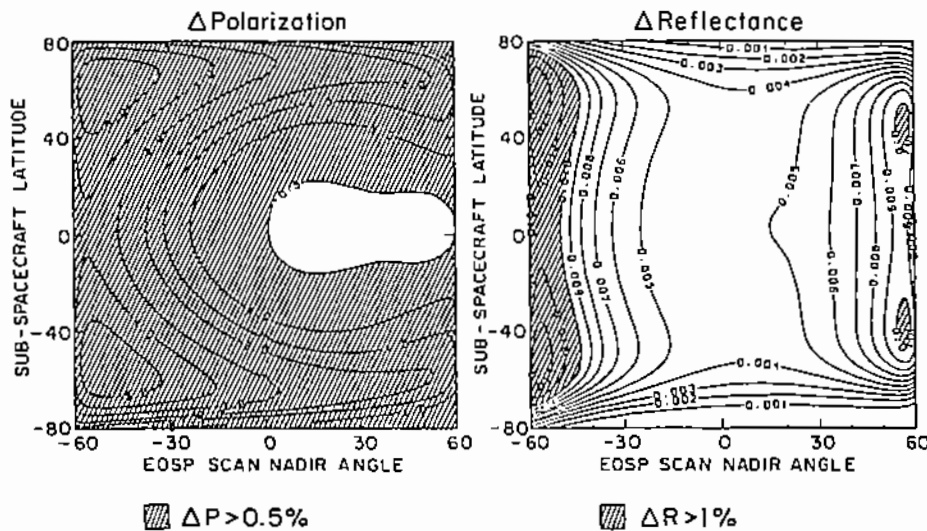


Fig. 9.4. Difference in the polarization and reflectance between clear atmosphere and added aerosol of optical thickness 0.1 for the full range of viewing geometries.

We simulate EOSP data for a vegetation-covered surface by using representative leaf refractive indices (Jacquemoud and Baret, 1990) and assuming that all diffuse leaf scattering (multiple scattering among leaves) is unpolarized (Vanderbilt *et al.*, 1985). For the tropospheric aerosol, we adopt aerosol properties corresponding to the continental model of WCP-55 (1983), viz., a sulfate component of log-normal distribution with geometric mean radius  $r=0.15 \mu\text{m}$  and size distribution width  $\sigma=1.5$ , and a dust component with  $r=0.5 \mu\text{m}$ ,  $\sigma=2.5$ , with number density 0.003 that of the sulfate component. The effective radius (Hansen and Travis, 1974) for the aerosol mixture is  $r_{\text{eff}} = 0.62 \mu\text{m}$  and the effective variance of the size distribution is  $v_{\text{eff}} = 0.30$ . Simulations for each of the twelve EOSP spectral bands are made for this aerosol for an optical thickness of 0.2 at 550 nm. The aerosol is distributed through the 300-mb layer just above the vegetation surface, and Rayleigh scattering by the atmosphere is included in the multiple scattering computations.

The simulated polarization for a  $15^\circ$  nadir angle and sub-spacecraft latitude of  $36^\circ\text{N}$  (phase angle  $38^\circ$ ) is shown in Fig. 9.3a (open circles) and compared with the polarization for the surface alone (squares) and the surface plus clear atmosphere (triangles). Rayleigh scattering dominates the polarization at the shorter wavelengths, with the aerosol causing partial depolarization compared to the clear atmosphere result. This difference is displayed (filled circles) in the lower panel of the figure with an expanded scale. Since the EOSP measurement accuracy for polarization is 0.2%, the depolarization caused by the aerosol at short wavelengths is easy to detect. At the longest wavelengths, the observed polarization is essentially that due to the surface, because of the decreasing scattering efficiency of the aerosols with increasing wavelength. Thus, the wavelength coverage allows easy separation of surface and aerosol polarization effects.

The simulated radiance is shown in Fig. 9.3b, for the same case as the polarization in Fig. 9.3a. As was true for the polarization, Rayleigh scattering dominates over surface reflection at the shortest wavelengths. However, the radiance is much less sensitive than the polarization to the addition of aerosols. Indeed, the optical depth 0.2 appears to be near the limit that can be measured over any surface using only the radiance. That conclusion is consistent with empirical results obtained using AVHRR measurements (Rao *et al.*, 1988).

A further illustration of the greater sensitivity of the polarization than radiance to aerosols is given in Fig. 9.4, which shows the change of polarization and radiance caused by an increase of aerosol optical depth 0.1 for the complete range of observing geometries at the single wavelength 410 nm. Since the absolute polarization error is less than 0.2%, any regime with a polarization change greater than 0.5% would have a substantial signal to noise ratio. A comparable signal to noise ratio

for the reflectance can at best be obtained only for extreme nadir viewing angles.

The aerosol size can also be retrieved from the spectral variation of the polarization, and with much less precision from the spectral variation of the radiance. Because the typical aerosol sizes are 0.1–1  $\mu\text{m}$ , there is a strong wavelength dependence of scattering efficiency, and hence optical thickness, throughout the visible and near infrared regions. Aerosols larger than those used for Figs. 9.3 and 9.4 maintain a measurable impact on polarization at longer wavelengths. Any aerosol distribution is also easily distinguished from optically thin or subpixel clouds: cloud opacity is relatively independent of wavelength over the EOSP wavelength range, while the aerosol opacity becomes negligible in the near infrared region.

As has been demonstrated with the studies using Venus polarimetry, the aerosol refractive index can also be deduced from polarization measurements. Those analyses have relied on being able to look at the same region from a range of scattering angles, or equivalently, a situation in which the aerosol structure and characteristics are uniform over a large horizontal extent. Accordingly, the scanning strategy proposed entails obtaining such multiple scattering angle coverage with along-track scanning on the polar, sun-synchronous Climatsat spacecraft, while using cross-track scanning on the inclined orbit spacecraft to provide daily global mapping.

Accurate cloud properties can be obtained from polarimetry as demonstrated by observations of other planets, simulations for terrestrial clouds, and near-infrared aircraft measurements (Coffeen and Hansen, 1974). Cloud-top height and total cloud optical thickness are primary cloud parameter objectives because of their first-order importance in describing the radiative effects of the cloud. Because of the great difference in polarization of light scattered by air molecules (Rayleigh scattering) and cloud particles, the degree of polarization in the ultraviolet region provides a simple measure of cloud top pressure. Figure 9.5 is a simulation for the 410 nm EOSP band, showing the varying effect of Rayleigh scattering for different cloud top pressures. The top panel is the polarization as a function of scan element for a uniform cloud of 10  $\mu\text{m}$  radius water droplets, with the cloud optical thickness 10 and the cloud top pressure 500 mb. The polarization peak at phase angle near 40° is the rainbow feature, while the strong increase for phase angles greater than about 70° is due entirely to Rayleigh scattering. Since the Rayleigh scattering optical thickness is proportional to the amount of atmosphere above the cloud, the increase of polarization at moderate phase angles varies with cloud top pressure. This is illustrated in the lower panel of Fig. 9.5, which shows the change in polarization caused by moving the cloud top from 500 mb to 400, 300 and 200 mb.

Cloud remote sensing algorithms have relied on the higher visible radiance levels of thicker clouds for generating an estimate of cloud optical depth (Rossow *et al.*, 1989). However, such an approach is often subject to ambiguity, especially for smaller optical thicknesses and small cloud

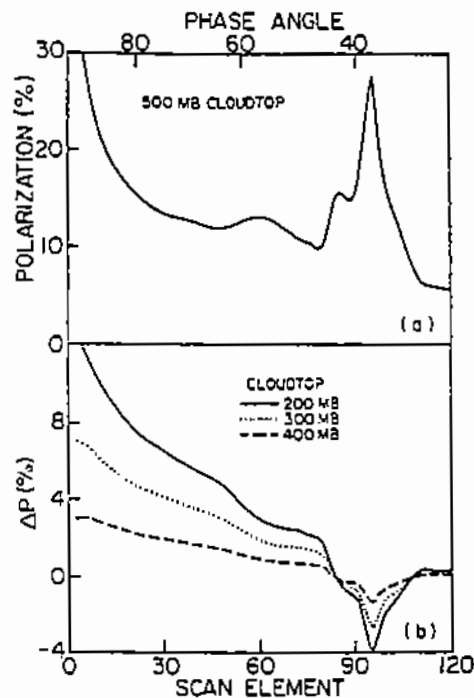


Fig. 9.5. Simulated polarization over an EOSP scan at the 410 nm band for a uniform cloud of optical thickness 10 and a cloudtop pressure of 500 mb (top panel). Differences in the polarization for 200, 300, and 400 mb cloudtop pressures compared to the 500 mb case are displayed in the bottom panel.

particle sizes. Moreover finite resolution of satellite measurements can lead to some radiance variability associated with partial coverage of the IFOV by clouds. Observations at near-infrared wavelengths, where water absorption is important, are potentially sensitive indicators of cloud particle size and optical depth (Hansen and Pollack, 1970); these indicators are not too sensitive to partial cloud cover effects (Han, 1992). Accordingly, techniques based upon multispectral radiances, including especially near-infrared bands, are being advanced (Nakajima and King, 1990; Han, 1992). Even greater sensitivity to cloud properties is provided by polarimetry. Polarization is usually more sensitive to cloud microstructure than is the intensity (Coffeen and Hansen, 1974); thus polarization measurements are particularly useful in detecting and characterizing optically thin clouds, which pose significant difficulties for algorithms employing intensity alone. Use of EOSP and MINT observations together allows for direct determination of partial cloud cover in the IFOV by measuring the relative contributions of Rayleigh and Mie scattering. With new advances in treatment of scattering by non-spherical particles, information about ice cloud particles may also be attainable from EOSP measurements.

Table 9.3 summarizes the estimated accuracies for the aerosol, cloud, and surface properties that EOSP will monitor. The uncertainties in a single 'pixel' retrieval can be substantially reduced by averaging the results over time and spatial scales of relevance to climate, such as monthly means at 500 km resolution. These EOSP accuracies are generally much higher than possible with current satellite instruments, such as the operational AVHRR instruments used for ISCCP analyses. For some quantities, such as cloud height, the Michelson Interferometer is capable of providing higher accuracy. We also note that recent experience with AVHRR data (Han, 1992) suggests that the precision of variations of cloud particle size and optical thickness from place to place and time to time can be much higher than the estimated absolute accuracy. Thus, because of the much better calibration and stability of EOSP compared to AVHRR the precision of the measured changes may be significantly better than our estimates. A summary of our error estimates for all the parameters, and a comparison with the requirements, is given in Table 7.4.

**TABLE 9.3. EOSP data product accuracies.**

	Single Field of View	Monthly 500 km Mean
<b>Aerosols</b>		
Optical Thickness	0.03	0.01-0.02
Particle Size	25%	10%
Refractive Index	0.05	0.02
<b>Clouds</b>		
Optical Thickness	10%	5%
Cloud-top Pressure	30 mb	15 mb
Particle Size	25%	10%
<b>Surface</b>		
Reflectance	0.02	0.01
Polarization	0.5%	0.3%

TABLE 10.2. MINT predecessor instruments.

<u>Instrument (Spacecraft)</u>	<u>Active period</u>	<u>Spectral range (resolution)</u>	<u>Mass</u>
IRIS (Nimbus-3)	Apr 1969	400-2000 $\text{cm}^{-1}$ (5 $\text{cm}^{-1}$ )	22 kg
IRIS (Nimbus-4)	Apr 1970 - Jan 1971	400-2000 $\text{cm}^{-1}$ (2.8 $\text{cm}^{-1}$ )	22 kg
IRIS (Mariner 9)	1971	200-2000 $\text{cm}^{-1}$ (2.4 $\text{cm}^{-1}$ )	22 kg
IRIS (Voyager 1)	Sep 1977 - Aug 1981	180-2500 $\text{cm}^{-1}$ (4.3 $\text{cm}^{-1}$ )	18 kg
IRIS (Voyager 2)	Aug 1977 - 1989	180-2500 $\text{cm}^{-1}$ (4.3 $\text{cm}^{-1}$ )	18 kg
TES (Mars Observer)	Sep - Oct 1992	200-1600 $\text{cm}^{-1}$ (5 $\text{cm}^{-1}$ )	15 kg

make it a valued benchmark in climate data that only recently is beginning to be fully exploited (Prabhakara, 1988, 1990). Other predecessor instruments were the Mariner-9 IRIS launched to Mars in 1971 (Hanel *et al.*, 1972b) and the notable Voyager-1 and Voyager-2 IRIS instruments, launched on interplanetary tours in 1977, that obtained detailed information on the atmospheric structure and composition of Jupiter, Saturn, Uranus and Neptune (Hanel *et al.*, 1981, 1983; Kunde *et al.*, 1982; Conrath *et al.*, 1987, 1989; Carlson *et al.*, 1992a,b). The several IRIS instruments have been of similar mass (20 kg) and have had similar performance characteristics with respect to spectral range and resolution. All performed well in space, with the Voyager IRIS instruments operating flawlessly over a 12 year time span. The Mars Observer TES (launched in September 1992) is the most recent of IRIS type space instruments (Christensen, *et al.*, 1992). Weighing 15 kg and having a somewhat coarser spectral resolution (5  $\text{cm}^{-1}$ ), TES incorporates the latest advances in detector and electronics technology and serves as the pattern of instrument design for MINT. Thus MINT incorporates key elements that contributed to the success of predecessor instruments, but uses state-of-the art detector and electronics technology. The 8 km field-of-view of the MINT pixel, combined with its contiguous 3-pixel wide along-track sampling, is an order of magnitude improvement over the 95 km resolution of Nimbus-4 IRIS.

The infrared spectrum emitted by the earth is formed of the essentially black-body thermal emission from the earth's surface, modulated by the spectrally discreet absorption and re-emission due to atmospheric gases and by the spectrally smoother variations in absorption, emission and scattering by clouds. As a result the outgoing thermal spectrum contains detailed information on the concentration and vertical distribution of atmospheric gases, cloud properties (including effective particle size and optical thickness), as well as the surface and atmospheric temperature structure. The prominent spectral features that appear in the clear sky thermal spectrum (Fig. 10.1) are the 15  $\mu\text{m}$   $\text{CO}_2$  band used primarily for temperature sounding, the 9.6  $\mu\text{m}$  ozone band, and the 7 to 8  $\mu\text{m}$   $\text{CH}_4$  and  $\text{N}_2\text{O}$  complex. Water vapor absorption spans the entire spectrum, being strongest for wavelengths less than 7  $\mu\text{m}$  and greater than 20  $\mu\text{m}$ . The relatively clear window region from 8 to 12  $\mu\text{m}$  contains information on tropospheric water vapor distribution and is also the region where the spectral signature of clouds is most apparent.

At each wavelength, the radiation emerging at the top of the atmosphere contains contributions that originate from different levels of the atmosphere. These contribution functions (Fig. 10.2) are determined by the atmospheric vertical distribution of the absorber, absorption coefficient strengths, and atmospheric temperature profile. For  $\text{CO}_2$ , since the absorber distribution and absorption coefficients are known, the contribution functions permit retrieval of the atmospheric temperature profile. With the temperature profile determined, the contribution functions are used to obtain information on the atmospheric concentration and vertical distribution of water vapor and ozone.

## 10. Michelson Interferometer (MINT)

*Andrew Lacis and Barbara Carlson, NASA Goddard Institute for Space Studies*

MINT is a Michelson Interferometer designed to measure the thermal emission from the earth at high spectral resolution ( $2\text{ cm}^{-1}$ ) over a broad spectral range ( $250\text{--}1700\text{ cm}^{-1}$ ,  $6\text{--}40\text{ }\mu\text{m}$ ) with contiguous 3-pixel wide ( $12\text{ mrad}$ ,  $8\text{ km}$  field of view) along-track sampling. MINT is particularly well suited for monitoring cloud properties (cloud cover, effective temperature, optical thickness, ice/water phase, and effective particle size) both day and night, as well as tropospheric water vapor, ozone, and temperature.

The key instrument characteristics that make MINT ideally suited for decadal monitoring purposes are: (1) high wavelength-to-wavelength precision across the full IR spectrum with high spectral resolution; (2) space-proven long-term durability and calibration stability; (3) small size, low cost, low risk instrument incorporating the latest detector and electronics technology. MINT also incorporates simplicity in design and operation by utilizing passively cooled DTGS detectors and nadir viewing geometry (with target motion compensation). MINT measurement objectives, instrument characteristics, and key advantages are summarized in Table 10.1.

MINT has a well founded heritage in space-proven instrument hardware (Table 10.2) with a thoroughly demonstrated concept for information retrieval (Conrath *et al.*, 1970; Smith, 1970; Chahine, 1974; Smith and Frey, 1990). The Nimbus-3 and Nimbus-4 IRIS instruments launched in 1969/1970 obtained a one-year long climatology of high spectral resolution ( $5\text{ cm}^{-1}/2.8\text{ cm}^{-1}$ ) Earth observations over the  $5\text{--}25\text{ }\mu\text{m}$  ( $400\text{--}2000\text{ cm}^{-1}$ ) spectral range (Hanel *et al.*, 1970, 1972a; Conrath *et al.*, 1970; Kunde *et al.*, 1974). The accurate calibration and high information content of this dataset

**TABLE 10.1. Michelson Interferometer (MINT)**

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### Measurement Objectives

Cloud properties: cloud cover, effective temperature, optical thickness, ice/water phase, effective particle size (all obtained day and night)

Water vapor: three levels in troposphere

Ozone: two levels in troposphere and one in stratosphere

Temperature: four levels in troposphere and surface temperature

Measurement precision required to determine interseasonal, interannual and decadal changes of all these parameters

### Instrument Characteristics

Spectral Range:  $250\text{--}1700\text{ cm}^{-1}$  ( $6\text{--}40\text{ }\mu\text{m}$ )

Spectral Resolution:  $2\text{ cm}^{-1}$

Field of View:  $12\text{ mrad}$  ( $8\text{ km}$ ) - same as EOSP

Detector:  $2\times 3$  array of uncooled deuterated triglycerine sulfate (DTGS)

Sampling: contiguous 3-pixel wide along-track sampling

### Key Advantages

Full IR spectral coverage with high resolution

High wavelength-to-wavelength precision (single detector)

Proven long-term durability and calibration stability; small size, low cost, low risk

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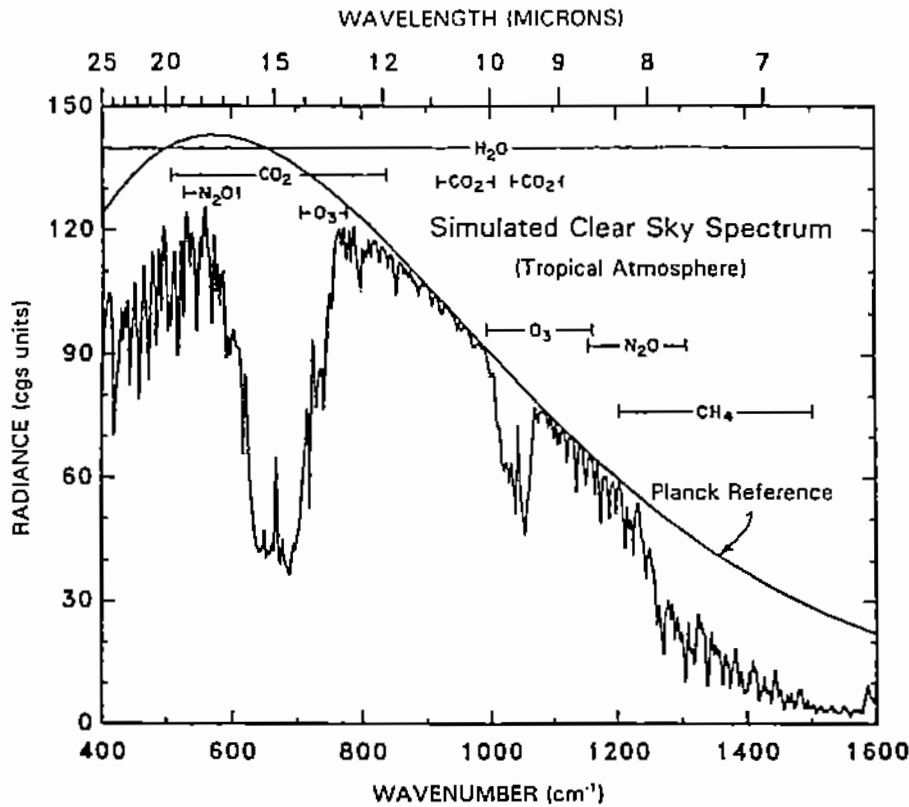


Fig. 10.1. Clear sky spectrum at  $3 \text{ cm}^{-1}$  (IRIS) resolution. The spectral locations of the principal absorption features are identified.

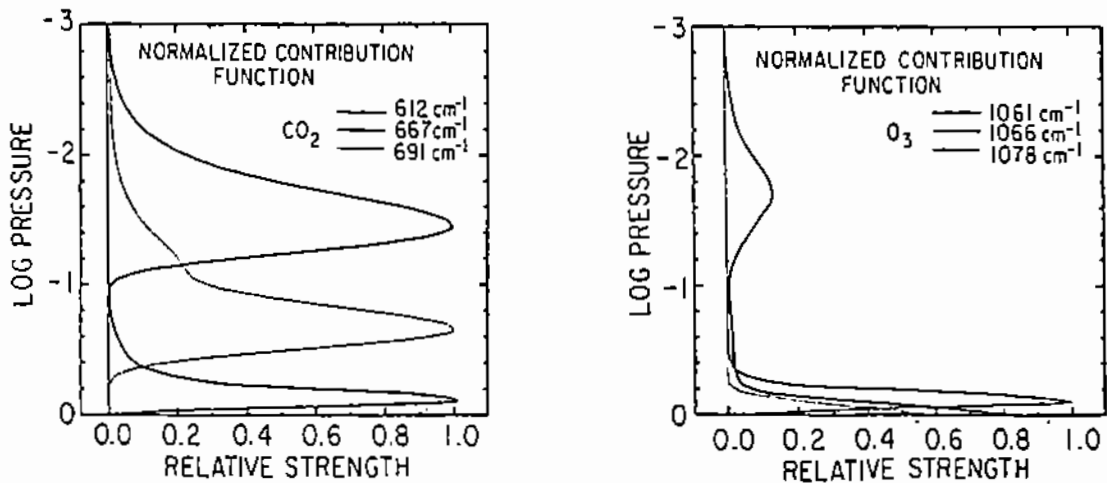


Fig. 10.2. Contribution (weighting) functions illustrating height and wavelength dependence of radiance emission level used in retrieval of height dependent profiles for temperature from the  $\text{CO}_2$  band (left) and ozone (right).



Each atmospheric constituent has a unique spectral signature that can be used to determine its atmospheric concentration and location. Furthermore, this spectral signature is spread over hundreds of wavelength points in the measured spectrum and is very strongly correlated in wavelength space. Instrumental noise, on the other hand, is uncorrelated, thus permitting unambiguous statistical extraction of small changes in absorber distribution that are not readily measurable with a discreet channel instrument. The capability for precise long-term monitoring of atmospheric constituents with MINT is tied to the very high wavelength-to-wavelength precision that is only possible with an interferometer type instrument. In the following, we illustrate the retrieval capabilities for MINT by using simulated Nimbus-4 IRIS spectra, since the spectral resolution, range, and instrumental noise characteristics are similar for the two instruments.

The spectral signature of clouds is formed by contributions of upwelling thermal radiation that is transmitted through the cloud, by thermal radiation emitted by the cloud, and to lesser extent, by the reflection of downwelling radiation that is incident on the cloud. Thus the cloud spectral signature is determined by the spectral dependence of the cloud radiative properties as well as the cloud and underlying temperature structure, which in the window region is essentially the surface temperature. Since the cloud radiative properties depend directly on the refractive indices of water and ice, the effective cloud particle size, and the cloud optical thickness, the measured infrared spectrum can be used to retrieve cloud liquid/ice phase, particle size and optical depth, including also the effective cloud temperature. Within the 8 to 12  $\mu\text{m}$  window region, clear sky spectra conform closely to the Planck spectral distribution. Thus clouds are detected and identified by their degree of departure from a Planck spectrum.

Liou *et al.* (1990) and others have shown that cirrus cloud properties can be derived from thermal infrared spectra. As shown in Fig. 10.3, the retrieval of cirrus cloud optical thickness information with MINT is possible over a broad dynamic range. A cirrus cloud of optical thickness  $\tau = 0.1$  is easily differentiated from the clear sky spectrum across a broad range of wavelengths, indicating that much smaller optical thickness would be detectable with data accumulation and statistical analysis. MINT can also discriminate among optical thicknesses as large as  $\tau = 5$  to 10. This is because the diffusely transmitted radiation persists for relatively large optical thicknesses even though the direct emission from the cloud becomes saturated at smaller optical depths. Similar behavior is exhibited by water clouds, but due to differences in the spectral dependence of refractive indices, the spectral signature of water clouds shows characteristic spectral differences that permit phase discrimination.

Besides optical depth, the cloud spectral signature is also strongly dependent on particle size. This is illustrated in Fig. 10.4 for a typical water cloud of optical depth  $\tau = 5$ , for effective particle sizes of 5, 10, and 30  $\mu\text{m}$ . The difference spectra in the lower portion of the figure show the relative changes in radiance for clouds of 5 and 30  $\mu\text{m}$  particles with respect to the 10  $\mu\text{m}$  particle cloud spectrum. The particle size spectral signature becomes more pronounced toward smaller particle sizes, while for very large particles the spectrum becomes more Planck-like in character. The estimated accuracy of effective particle size retrieval of a water cloud is about 5 percent, thus 0.5  $\mu\text{m}$  for 10  $\mu\text{m}$  particles.

Relative cloud height changes of order 5 to 10 mb can also be detected in a single comparison of two spectra. The spectral signature for a 10 mb cloud height change is shown in the lower portion of Fig. 10.5 for a cirrus cloud of optical thickness  $\tau = 1$ . Averaging over many spectra would reduce the uncorrelated noise component relative to the spectral signature and allow a cloud height accuracy of the order of 1 mb for seasonal-mean cloud height determination.

MINT sensitivity to changes in atmospheric water vapor distribution is shown in Fig. 10.6. Here, the upper tropospheric water vapor between 300-700 mb is increased by 10 and 20 percent and the spectral differences compared to a standard reference profile. While the spectral signature of

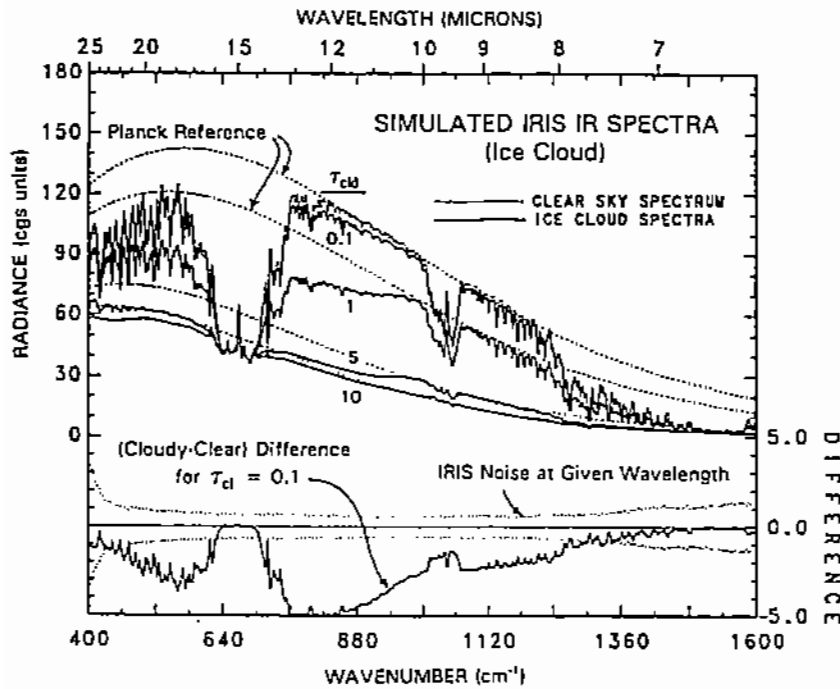


Fig. 10.3. Optical depth dependent spectral signatures of ice clouds. The difference spectrum between clear sky and optically thin ( $\tau = 0.1$ ) ice cloud in the lower portion of the figure shows that MINT will detect sub-visible cirrus.

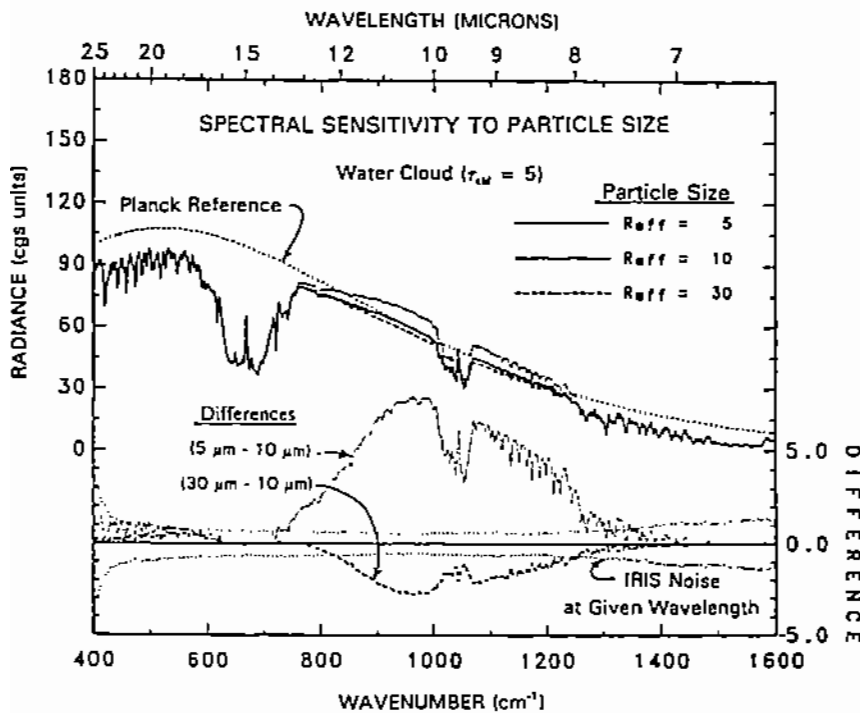


Fig. 10.4. Spectral sensitivity to particle size variations in a water cloud. The difference spectra in the lower portion of the figure shows the feasibility of MINT retrieval of cloud particle size.

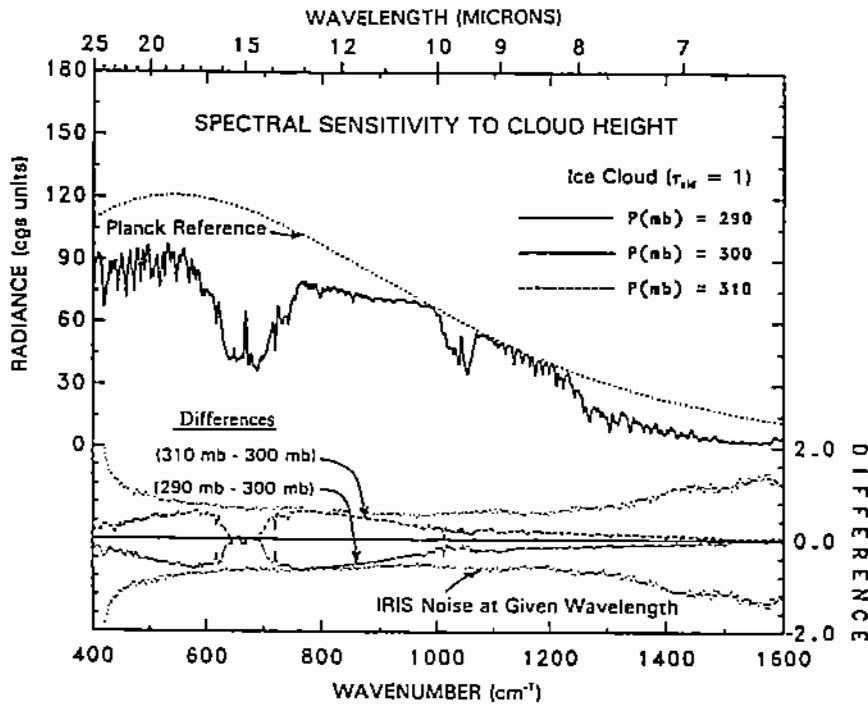


Fig. 10.5. Spectral sensitivity to cloud height variations. The difference spectrum in the lower portion of the figure shows that 10 mb cloud-height variations are detectable within the noise level of a single IRIS measurement. The performance of mint will be similar but with higher spatial resolution.

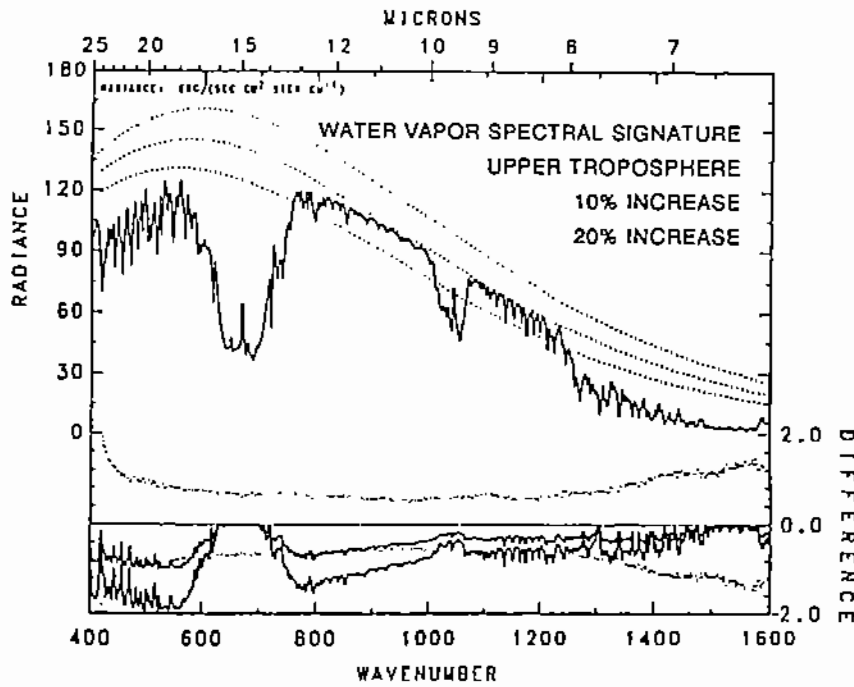


Fig. 10.6. Spectral sensitivity to changes in tropospheric water vapor amount. The difference spectra in the bottom of the figure demonstrate that a 10% change in upper tropospheric water vapor will be detectable in a single MINT measurement.

water vapor is spread across the entire spectrum, the 10 percent water vapor increase in the upper troposphere produces a barely noticeable (less than 1 percent) reduction in absolute radiance at any one wavelength. To reliably detect this change with standard channel-instrument technology would require unrealistic precision and calibration. However, as shown on an expanded scale in the difference spectrum at the bottom of the figure, this change in water vapor is clearly detectable through a single comparison of two clear-sky spectra because, in effect, the signals of all wavelengths are combined to produce a different spectrum shape. Sensitivity to atmospheric location of the water vapor change is also contained in the spectral signature. For example, the spectral change near  $20\ \mu\text{m}$  ( $400\text{--}600\ \text{cm}^{-1}$ ) that is so prominent for upper tropospheric water vapor, is virtually absent for water vapor changes near the ground. Furthermore, the differential sensitivity at the low and high frequency wings of the  $15\ \mu\text{m}$   $\text{CO}_2$  band to overlapping water vapor absorption (Ackerman, 1979; Clough *et al.*, 1989a) provides more independent observational constraints on the retrieval of temperature and water vapor profiles than is possible using measurements of only the high frequency wing. In similar fashion, spectral differences measured within the  $9.6\ \mu\text{m}$  ozone band are used to detect changes in tropospheric and stratospheric ozone amount. The known variation of water and ozone absorption with wavelength allows separation of atmospheric and surface effects, which allows MINT to obtain much better measurements of surface temperature and emissivity than possible with discrete channel instruments.

The estimated accuracies of MINT data products are summarized in Table 10.3. Because the spectral signatures of the measured quantities (e.g., effective cloud particle size, phase, optical thickness, atmospheric and surface temperature, water vapor, ozone) are accurately known, they can be statistically extracted from the measurement noise. Thus errors representative of single "pixel" retrievals can be significantly reduced by averaging multiple views of the same and nearby regions, or obtaining monthly and seasonal averages. As is the case for EOSP, the accuracies obtainable with MINT are generally higher than with current operational satellite instruments, which is attributable to the high wavelength-to-wavelength precision of the MINT measurements. The accuracy of the MINT retrievals can be further improved through greater averaging. Moreover, because of the high degree of calibration stability of MINT (demonstrated by its predecessors) the simultaneous measurements by MINT instruments on two satellites permits acquisition of a homogeneous calibrated climatology of MINT data products on decadal time scales. A summary of our error estimates for all the parameters, and a comparison with the requirements, is given in Table 7.4.

**TABLE 10.3. Estimated MINT data product accuracies.**

	Single Field of View	Monthly 500 km Mean
<b>Clouds</b>		
Effective Temperature	1-2K	<1K
Optical Thickness	12%	5%
Particle Size	9%	5%
Phase (confidence)	99%	99%
<b>Water Vapor</b>		
300-700 mb	10%	5%
700-1000 mb	<10%	<5%
<b>Ozone</b>		
Tropospheric Mean	15%	<10%
Stratospheric Mean	10%	<5%

## 11. Orbit and Sampling Requirements: TRMM Experience

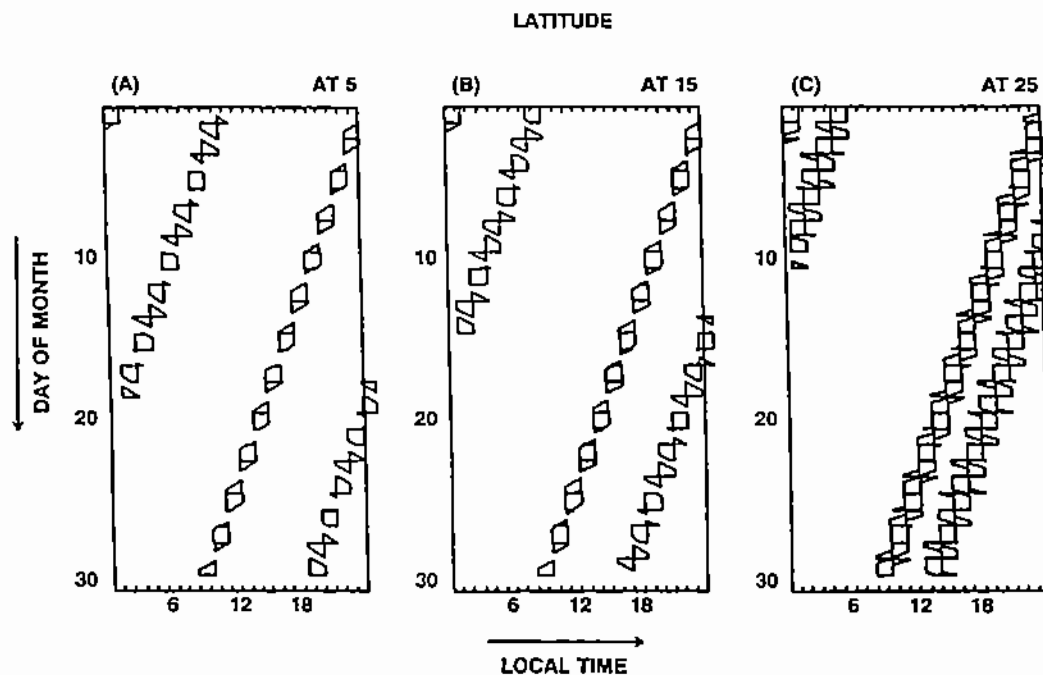
Gerald North, Texas A & M University

**Introduction.** The Tropical Rainfall Measuring Mission (TRMM) concept originated in 1984 (Simpson *et al.*, 1988). Its overall goal is to produce datasets that can be used in the improvement of general circulation models. A primary objective is a multiyear data stream of monthly averages of rainrate over 500 km boxes over the tropical oceans. Vertical distributions of the hydrometers, related to latent heat profiles, and the diurnal cycle of rainrates are secondary products believed to be accessible. The mission is sponsored jointly by the U.S. and Japan. TRMM is an approved mission with launch set for 1997. There are many retrieval and ground truth issues still being studied for TRMM, but here we concentrate on sampling since it is the single largest term in the error budget.

The TRMM orbit plane is inclined by  $35^\circ$  to the equator, which leads to a precession of the visits to a given grid box through the local hours of the day, requiring three to six weeks to complete the diurnal cycle, depending on latitude. For sampling studies we can consider the swath width to be about 700 km. Figure 11.1 shows a visit sequence (local time versus day of month) for a month for the TRMM satellite (Shin and North, 1989). This illustrates the latitude dependence of the sampling sequence.

**Types of Sampling.** TRMM sampling studies have been of three types:

1) Given a dataset of rainrates collected from a ground site or for a special observing period, such as the GATE, we can "fly" an ensemble of imaginary TRMM satellites over the data and see how the sampling by the satellite ensemble agrees with the actual average rainrate for the month. This approach was pursued by McConnell and North (1987) and Kedem *et al.* (1990), who found that the errors for a 280 km square box over a three week period were of the order of 10%.



Source: Shin and North (1988)

Fig. 11.1. The visiting sequences and fractional coverages through a month for the TRMM orbit (300 km altitude and  $35^\circ$  inclination) for different latitudes [(a) at  $5^\circ$ , (b) at  $15^\circ$ , (c) at  $25^\circ$ ].

2) We can make models of the rainrate field, tuning them to the GATE data, then "fly" ensembles of satellites over the data field to check the error. The advantage of the models is that we can make the gridbox larger and we can change parameters to represent the differences in climatology over different regions and seasons. The first such model was formulated by Laughlin (1981) as a simple first order autoregressive model of the area averaged rainrates. An extension of Laughlin's method was presented with many numerical results for TRMM by Shin and North (1989). A very comprehensive rainfield model was constructed by Bell (1987) and TRMM calculations were presented later by Bell *et al.* (1990). Bell's model is a fully two dimensional random field simulation which includes all the spatial-temporal second moment statistics and the correct probability distribution function for the rainrates as tuned from GATE.

3) The last class of studies makes use of the spectral form of the mean square error (MSE). North and Nakamoto (1989) showed that the MSE can be written as an integral of the space-time spectral density of the rainrate field, weighted by a filter which depends only on the sampling design, be it single or multiple satellite or rain gauges (North *et al.*, 1991; North *et al.*, 1992). This last formulation is particularly useful since we can imagine optimally weighting the data from different sources to form the best estimate of the space-time averages.

Root mean square error results (monthly average rainrate) for various satellite orbit parameters are shown in Fig. 11.2 as percent of the mean. We see that the errors for TRMM (inscribed box) are 10 to 12%. A sun-synchronous satellite at 800 km altitude would give only 10% errors. (TRMM has a low altitude to achieve high resolution of the individual field-of-views and to conserve radar power.)

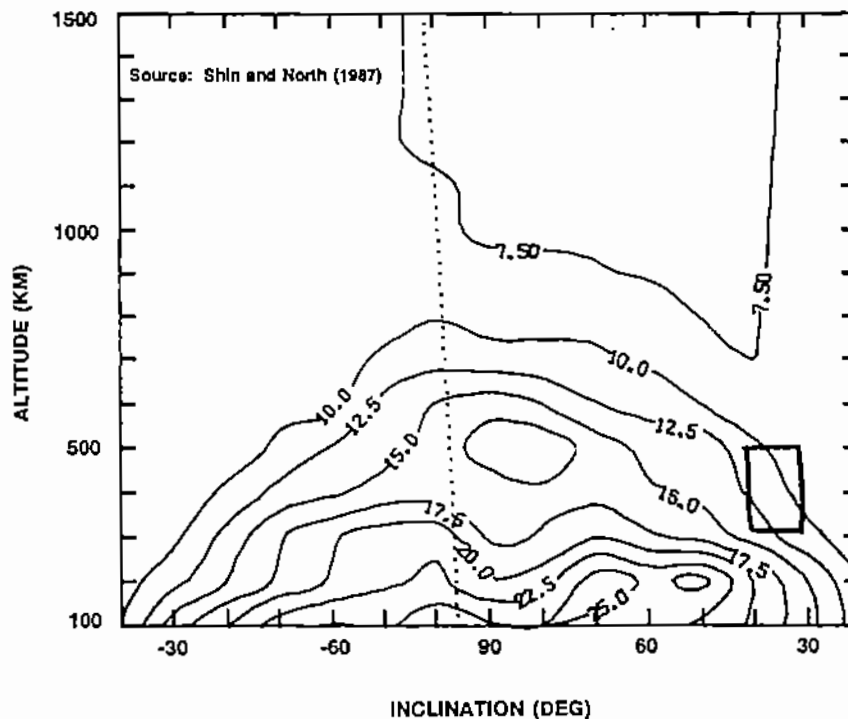


Fig. 11.2. Distribution of rms sampling errors in monthly mean rainfall rate (percent of mean value) as a function of satellite altitude and orbit inclination (Shin and North, 1987).

**Main factors determining sampling errors.** The studies so far have indicated that the main factors determining sampling error are the autocorrelation time of the grid-box area averaged rainrate field and the variance of the grid-box averaged rainrate. Autocorrelation times for rainrates for 500 km boxes tend to be about 10 or 12 hours which is comparable to the revisit time for the satellite (at the equator). Revisit configurations of this type will lead to approximately 10% errors. The errors can obviously be reduced substantially by introducing data from a separate satellite, say a polar orbiter. North *et al.* (1992) showed that optimally combining data from the DMSR microwave radiometer with TRMM leads to errors of the order of 6%, which is probably comparable to other errors in the measurement process. The root mean square error in percent is proportional to the ratio of standard deviation to the mean for the area averages. Hence, we prefer areas with small fluctuations in their area averages. For GATE this ratio appears to be about 1.25.

The autocorrelation time increases with grid box area in the tropics (e.g., Bell *et al.*, 1990). Similarly the variance of area averages decreases smoothly as a function of grid box size (Shin and North, 1989). Hence, use of large averaging boxes reduces sampling error in several ways, including the fact that small boxes are missed more often by the swath. While this has not been thoroughly studied, there are likely to be useful tradeoffs between larger areas and shorter averaging times, especially when two or more satellites are used.

**Outstanding estimation issues.** Most of the TRMM studies are tuned in one way or another to the GATE dataset. Two studies (Shin *et al.*, 1990; Shin and North, 1991) suggest that GATE is reasonably representative of the important statistical quantities over the tropical Pacific. However, both studies were essentially qualitative and clearly more work needs to be done.

Extraction of the diurnal cycle is not a trivial matter, since there are severe sampling errors in trying to estimate its amplitude. Bell and Reid (1993) have provided some preliminary indication of these difficulties.

Various aliasing problems arise because of the interaction between the sampling of the diurnal cycle and some natural oscillations in the tropics such as the Madden-Julian waves which have a period of 40-50 days. It appears that to correct for these we will need to introduce other data on the phase and amplitude of the waves.

**TRMM and Climsat.** TRMM and Climsat have several sampling properties in common: inclined orbit, use of data from multiple sources. My preliminary very crude estimate is that Climsat will have smaller sampling errors than TRMM because the fields being measured have longer autocorrelation times. For example, Cahalan *et al.* (1979) showed that the outgoing IR has autocorrelation times of the order of a day or two for 250 km boxes. Nevertheless, it is advisable to construct random field models of the desired field and conduct observing system simulation experiments. While using data from GCMs is useful, it is not helpful for some of the issues at scales that are smaller in space than the grid size of the GCM. These smaller scales will have smaller autocorrelation times and this could be crucial. Hence, I recommend the construction of specific random field models for the several hundred km scale. These can be stochastic models as opposed to real dynamical mesoscale numerical models. The main concern is that the space-time correlation properties be faithfully simulated.

## 12. Satellite Orbit and Data Sampling Requirements

*William Rossow, NASA Goddard Institute for Space Studies*

Climate forcings and feedbacks vary over a wide range of time and space scales (cf., Peixoto and Oort, 1992). The operation of non-linear feedbacks can couple variations at widely separated time and space scales (e.g., Barnett, 1991) and cause climatological phenomena to be intermittent (Lorenz, 1990). Consequently, monitoring of global, decadal changes in climate requires global observations that cover the whole range of space-time scales and are continuous over several decades. The sampling of smaller space-time scales must have sufficient statistical accuracy to measure the small changes in the forcings and feedbacks anticipated in the next few decades (see Section 3 above), while continuity of measurements is crucial for unambiguous interpretation of climate change. Shorter records of monthly and regional (500-1000 km) measurements with similar accuracies can also provide valuable information about climate processes, when "natural experiments", such as large volcanic eruptions or El Ninos occur. In this section existing satellite datasets and climate model simulations are used to test the satellite orbits and sampling required to achieve accurate measurements of changes in forcings and feedbacks at monthly frequency and 1000 km (regional) scale.

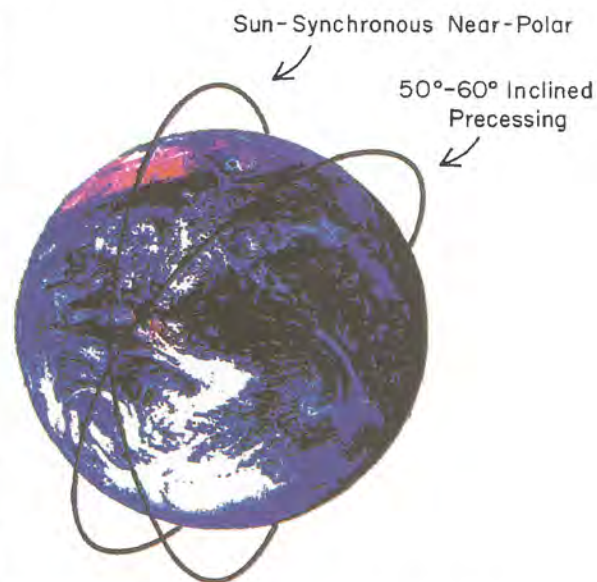
### Orbit Selection - Coverage and Sampling Frequency

The geographic coverage and sampling frequency of satellite observations are principally determined by the orbit and are the leading criteria for orbit selection. Other important selection criteria are instrument spatial resolution, the pattern of coverage of Earth's surface, the range of solar illumination geometries encountered, payload mass and mission lifetime. The payload mass that can be orbited by a particular launch vehicle is larger for lower altitude orbits; larger launch vehicles cost more than smaller launch vehicles. The instrument mass and cost required to attain a particular spatial resolution are lower in lower altitude orbits. Satellite mission lifetime is strongly limited by atmospheric drag in low (< 400 km) altitude orbits and by radiation damage rates in high (> 1000 km) altitude orbits.

All of these issues have been studied thoroughly for previous satellite missions and have also been considered in selecting possible orbits for Climsat, but the focus here is on the two most important requirements for monitoring climate changes: complete global coverage and unbiased sampling of diurnal variations. The observing system proposed for Climsat that meets these requirements has the same set of instruments in two orbits: a near-polar sun-synchronous orbit and an inclined and precessing orbit (Fig. 12.1). Orbital altitudes in the range of 500-700 km allow for high enough spatial resolution with a small payload mass and for mission lifetimes  $\geq 5$  years.

In the atmosphere, diurnal variations are the shortest periodic variation with significant amplitude (cf., Peixoto and Oort, 1992). These variations also interact with the daily variation of solar illumination and the surface to alter several key climate forcings and feedbacks. Emphasis is therefore placed on proper sampling of diurnal

### Climsat Orbit Requirements



**Fig. 12.1.** Required satellite orbits for the Climsat observing system.



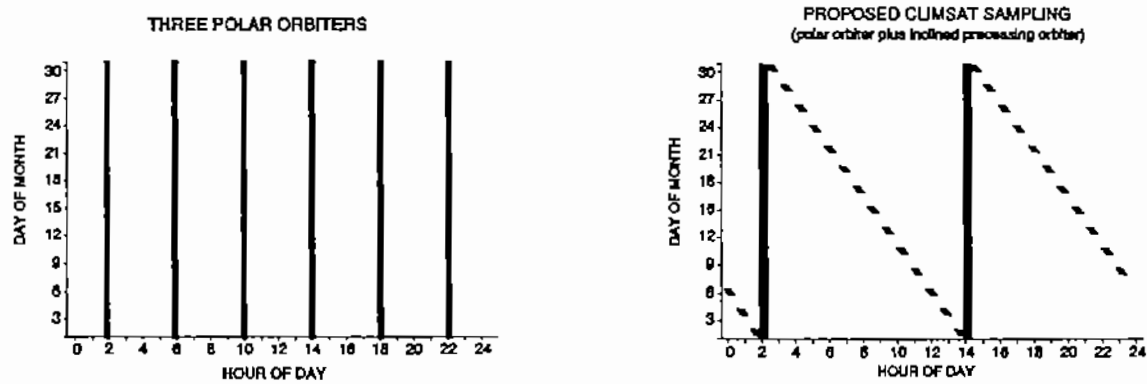


Fig. 12.2. Two alternative sampling strategies for adequate diurnal sampling.

variations, because it produces the strictest requirements. Proper diurnal sampling insures proper sampling of larger synoptic and planetary wave motions as well.

Global coverage and diurnal sampling cannot be satisfied by observations from one satellite (cf., Salby, 1982). A satellite in a polar orbit can view the whole Earth because of Earth's rotation, but the sampling frequency is only twice per day for orbital altitudes between 400-1000 km. The view from a satellite in an equatorial orbit is limited to low latitudes, but the sampling frequency can be more than 10 times per day. Geostationary orbits are special cases, where the view is restricted in both longitude and latitude, but the sampling frequency is limited only by instrument capability.

Figure 12.2 illustrates the sampling from two sets of orbits that provide global observations which adequately resolve diurnal variations. The simplest, direct method requires three sun-synchronous polar orbiting satellites with overflight times about four hours apart (Fig. 2, left panel), each providing two daily samples separated by 12 hours local time (Salby, 1982, 1988b, 1989). The major drawback of this approach for Climsat is that such polar orbits do not provide lower latitude coverage for the SAGE observations. SAGE, unlike most other instruments, must view the sun or moon at Earth's limb (see Section 8); this viewing geometry constrains observations to high latitudes from a polar orbit.

The observing scheme proposed for Climsat (Fig. 12.2, right panel) has only two satellites: one in an inclined orbit which precesses relative to the sun and one in a sun-synchronous polar orbit. The precessing orbit, inclined 50-60° to the equator, provides daily observations at two local times, separated by 12 hours, that vary slowly during the month (slanting lines). Observations from this orbit provide a statistical sample of diurnal variability at all latitudes where it is significant (McConnell and North, 1987; Shin and North, 1988; Bell *et al.*, 1990). The sun-synchronous orbit provides two daily observations over the whole globe at fixed diurnal phases, which allows for separation of diurnal variations from other oscillations with periods near one-half month (Harrison *et al.*, 1983). A similar sampling scheme was successfully used in the ERBE mission (Brooks *et al.*, 1986).

When observations are made in the nadir direction from this pair of orbits over one day, they cover the globe with an effective spacing of about 500-1000 km; Fig. 12.3 shows the orbits projected onto Earth's surface, called the ground tracks. The polar orbiter completes about 14 orbits per day with ground tracks that can be precisely repeated or their longitude can oscillate slightly over several days. The inclined orbiter also completes about 14 orbits per day, but the ground track precesses 5-6° of longitude per day so as to sample diurnal variations. This arrangement of orbits also permits solar occultations at all latitudes for SAGE (Fig. 12.4 shows the distribution of observations). Lunar occultations by SAGE III will increase the density of observations by about 50% over that shown in Fig. 12.4.

1 Day's Ground Tracks for Polar & Inclined Orbiter

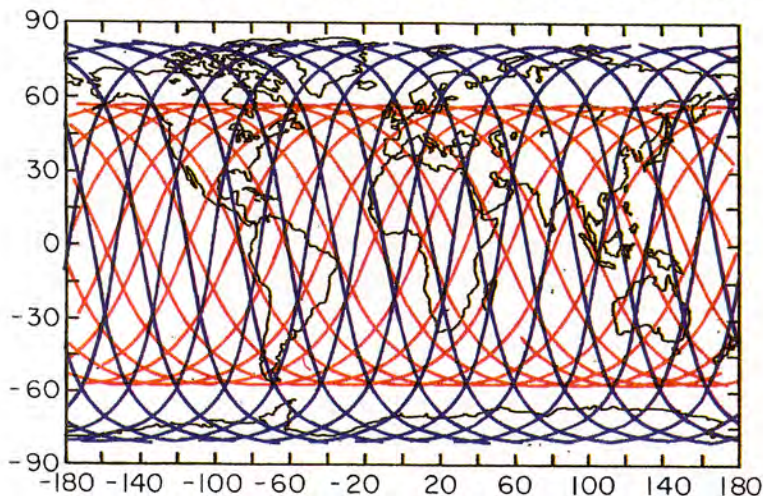


Fig. 12.3. One day's orbit ground tracks for polar (blue) and inclined (red) orbiters.

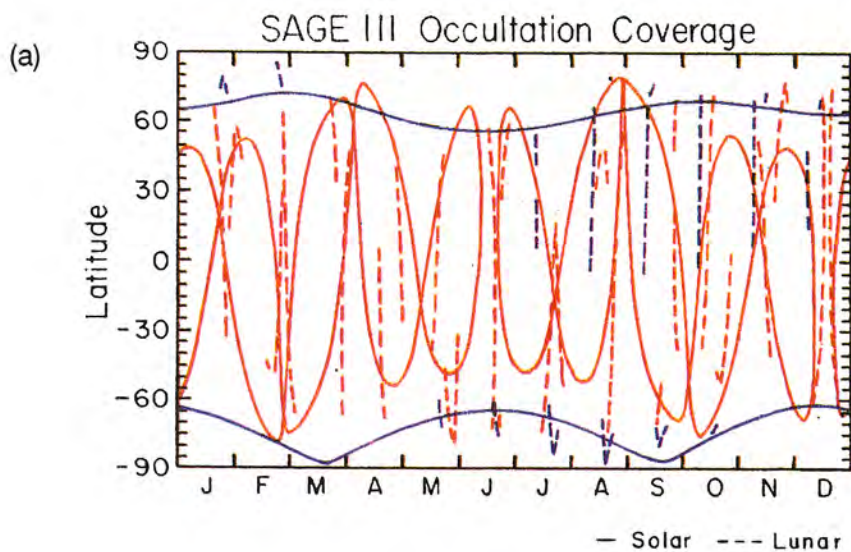
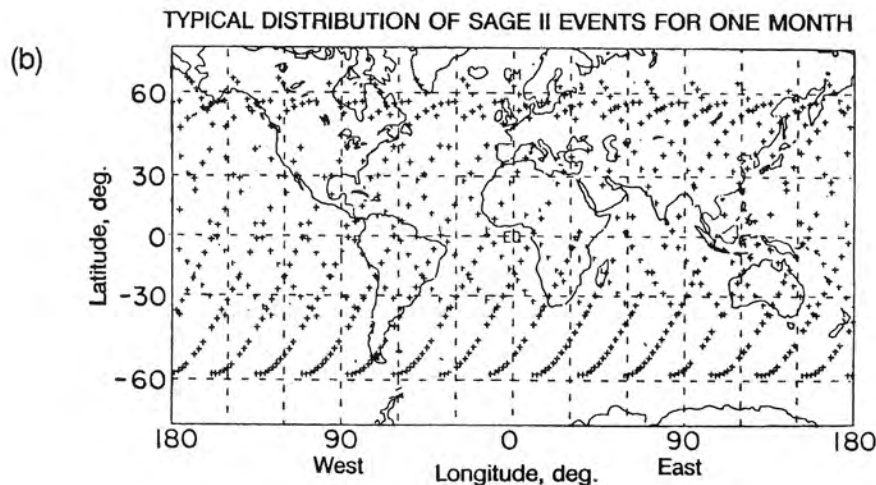


Fig. 12.4. (a) SAGE III solar and lunar occultation coverage over one year. Polar orbiter in blue and inclined in red. (b) typical SAGE sampling for one month from single satellite (inclined orbit, solar occultation). Lunar occultation increases density of observations about 50 percent; polar orbiter adds high latitude observations.



### Tests of Climsat Sampling

To test the Climsat observing strategy, real global observations and GCM calculations of several quantities are sampled using actual time records of the satellite ground tracks illustrated above. Samples are collected into global maps and averaged over time and space. Sampling errors are estimated from the differences between the monthly, regional mean values obtained from the sampled and original (taken to be "truth") datasets. The sampling test using real observations directly determines the accuracy of Climsat measurements of monthly, regional averages in the presence of realistic variations in time and space (cf., Section II). The sampling test using a GCM simulation of transient climate change allows a direct test of climate change detection, where the key problem is measuring the change in the presence of large natural variability (e.g., Oort, 1978 and Hansen and Lebedeff, 1987, used GCM simulations to test sampling, cf., Section I).

Ground tracks are from NOAA-9 (polar orbiter) and ERBS (inclined orbiter), giving positions every five seconds (about 30 km) over one month. The global observations are high resolution (30 km) measurements of cloud and surface properties every three hours for two Januarys and two Julys, obtained by the International Satellite Cloud Climatology Project (ISCCP) from weather satellite data (Rossow and Schiffer, 1991). Another dataset contains daily satellite measurements of humidity profiles at about 250 km spacing over the globe.

The climate change simulation is performed with the GISS GCM (Hansen *et al.*, 1983), which has  $8^\circ \times 10^\circ$  horizontal resolution and nine levels in the troposphere. The experiment simulates the transient climate changes produced by a linear increase of greenhouse gases (Scenario B, Hansen *et al.*, 1988); the climate change between 1958 and 2005 is used to test the Climsat sampling, since the global mean temperature change of  $0.8^\circ\text{C}$  is similar to the projected change from 1995 to 2015. Samples are collected from three hourly distributions of surface air temperature and vertical profiles of atmospheric temperature and specific humidity in the summers of 1958 and 2005. Sub-grid variations are represented by a bi-linear interpolation among the nearest model grid values to each sample point. In addition, random noise is added to each sample to represent both smaller scale variations and measurement errors: a Gaussian distribution is used, truncated at four standard deviations from the peak, with one standard deviation equal to  $2^\circ\text{C}$  for temperatures and equal to 30% of the local mean value for specific humidities at individual locations and altitudes.

Nadir observations are sampled at a spacing of about 30 km along the ground tracks. To simulate the same statistical weight obtained from multiple fields-of-view (FOV), an additional 6-9 samples around the nadir point are collected from the ISCCP dataset, but not from the GCM. Cross-track scanning is also tested on the GCM data by collecting about 200 points equally spaced on a line perpendicular to the satellite track at each nadir point. Since both the ISCCP and GCM datasets are composed of global maps at three-hour intervals, about 2200 nadir point samples are collected from each map.

In the tests using the ISCCP data, samples are taken directly from the population of individual satellite image pixels in the ISCCP dataset, so there is no "measurement error". Essentially, the sampling procedure isolates a subset of the ISCCP pixels (themselves, a sample of the original satellite measurements in FOVs about 5 km in size) that are concentrated at the locations and times defined by the orbit ground track time record. Monthly mean values obtained from the subset are compared to averages over the whole ISCCP population.

Sampling tests were conducted for surface temperature and reflectance, column abundances of ozone and water vapor, vertical profiles of temperature and specific humidity in the troposphere and stratosphere, and cloud properties. For brevity, only the results for cloud amount, surface air temperature and tropospheric humidity are shown. Cloud amount is highlighted because its very large natural variability in both space and time makes it one of the most difficult quantities to monitor

accurately. Surface temperature is tested because it has been the primary variable monitored for change and has the best understood sources of error. Water vapor is included both because it is highly variable (though not as variable as cloud cover) and difficult to measure, especially in the upper troposphere, so a large rms measurement error of 30% is included for each sample. The results show that the Climsat sampling is more than adequate to monitor likely changes in these quantities.

**Sampling Clouds.** Cloud amount is determined by counting the fraction of satellite FOVs (pixels) in a map grid cell that are inferred to contain clouds. In other words, the cloud amount for a single pixel is either 0 or 100%. For ISCCP the original FOVs of about 5 km size have been sampled to a spacing of 30 km; however, this sampling preserves the statistics of the original radiance variations (S  ze and Rossow, 1991a,b). Cloud amount is determined for a map grid with a resolution of about 280 km and has been shown to be accurate to within 5–10%, even for the most difficult cases (Wielicki and Parker, 1992; Rossow and Garder, 1993).

The frequency distribution of cloud amount, as determined from the ISCCP three-hourly data, is bimodal (Rossow and Schiffer, 1991). The bimodal shape (Fig. 12.5, left panel) is nearly constant for data resolutions of 30–280 km, where only about 15–25% of the cases represent cloud cover variations at scales < 280 km (Rossow and Garder, 1993).

The bimodal distribution of cloud amounts means that the natural variability of cloud cover is very large and that sampling error can be very large, since the distribution can be thought of as a probability distribution for a single sample (Warren *et al.*, 1986, 1988). The standard deviation of the distribution in Fig. 12.5 is about 30–35% (Warren *et al.*, 1986, 1988 give values of about 40%), so that more than 1000 samples are required to reduce the sampling uncertainty below 1% (cf. Warren *et al.*, 1986, 1988). Thus, a test of the Climsat sampling on cloud amount is a very strict test.

The accuracy of the monthly mean cloud amount determined from a nadir-viewing, non-scanning instrument in the Climsat orbits is shown on the right side of Fig. 12.5 as the frequency distribution of the sampling errors in individual map grid cells. Reducing the map grid resolution from 2.5° to 10° narrows the range of errors (e.g., the standard deviation of the errors for January 1987 decreases from 7.8% to 3.3%) as does increasing the averaging time period from one month to one season (standard deviations for three month averages decrease to 4.7% for 2.5° map grid and to 2.1% for a 10° map grid). The sampling error for global, seasonal mean cloud amounts from the Climsat orbits is less than 0.5%.

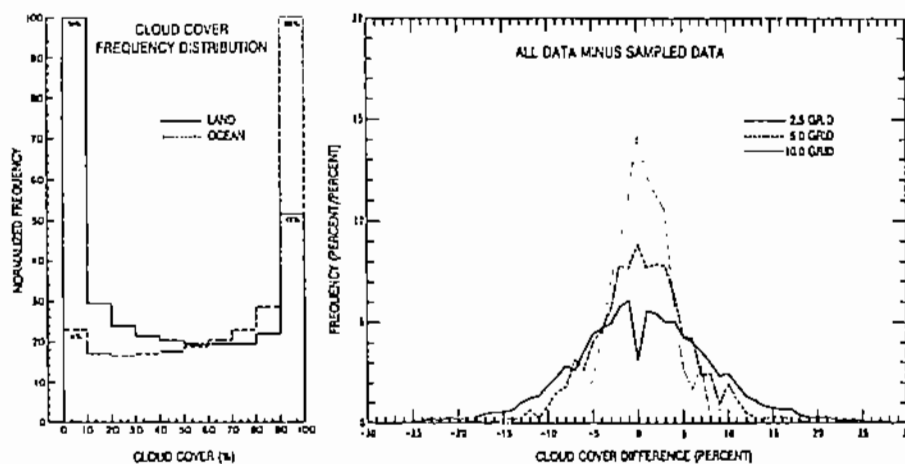
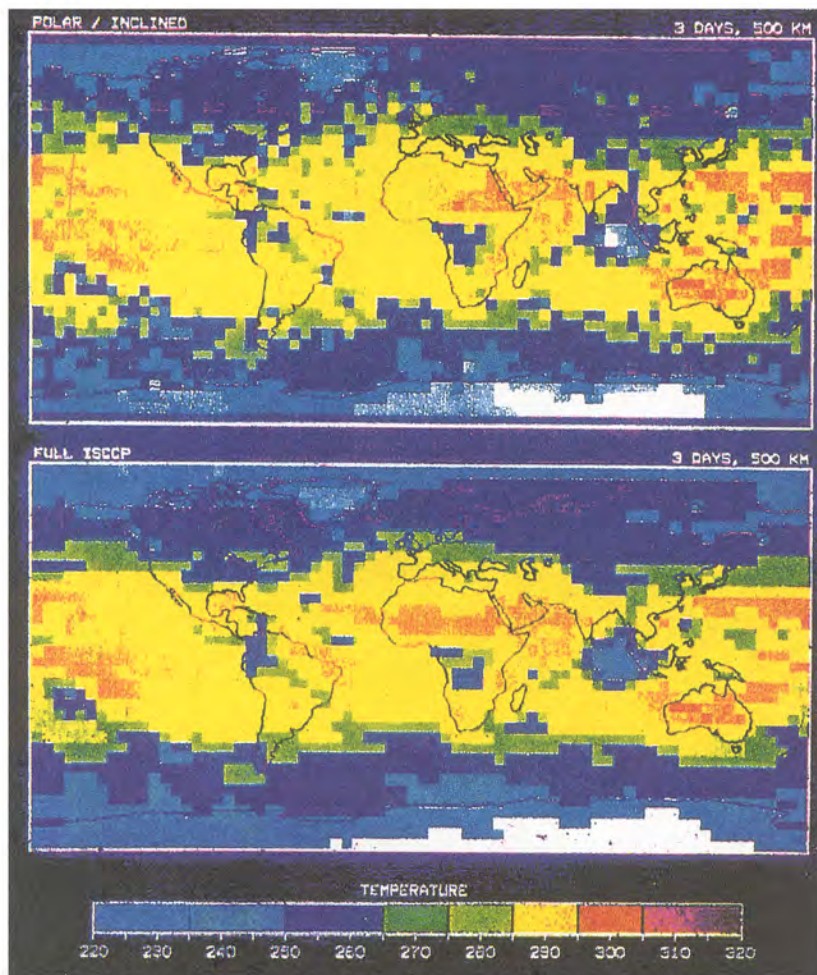


Fig. 12.5. Cloud cover frequency distribution for land and ocean and distribution of differences in monthly regional mean values produced by non-scanning sampling from Climsat orbits.



**Fig. 12.6.** Cloud top temperatures obtained by non-scanning samples from Climatsat orbits over three days and by the 30 km sampling from the combination of geostationary and polar orbiting satellites used by ISCCP.

The magnitude of errors associated with diurnally biased sampling is assessed by comparing the cloud amount from the full ISCCP dataset to that determined only from the polar orbiter measurements (cf., Salby, 1988b). Bell *et al.* (1990) have considered the sampling bias from an inclined orbit similar to proposed for Climatsat (cf., Section II). Geographic and seasonal variations of both the amplitude and phase of diurnal changes of cloud amount produce a wide range of bias errors, from about -20% to +10%. Cloud variations in midlatitudes are predominately caused by synoptic scale motions, particularly in winter, so that the diurnal-bias error is generally < 5%; however, the predominance of convective scale cloudiness at low latitudes leads to a systematic bias of about 5 - 10% in tropical cloud amounts. Since climate changes may appear both as changes in total cloud amount or in the amplitude or phase of diurnal cloud variations, adequate diurnal sampling is critical for interpreting observed changes.

Cloud top temperatures are, generally, much less variable at smaller scales than cloud cover. Figure 12.6 compares the geographic distribution of cloud top temperatures, accumulated over a three day sampling period and averaged over 500 km, with the corresponding results from the full resolution (3-hour, 30 km) ISCCP dataset. Such a comparison is a more extreme sampling test because the accumulation period (3 days) is much shorter and the spatial resolution (500 km) higher than required by Climatsat objectives. The good agreement between the two datasets is readily apparent. The rms regional (10° resolution) error of seasonal means is < 1.5°C, which is about an order of magnitude smaller than the average geographic variations. The sampling error of the global, seasonal mean is < 0.3°C.

**Sampling Surface Temperature and Atmospheric Humidities.** A direct test of climate change detection is provided by using the orbital ground tracks to sample the GISS GCM simulations of changes in the summer climate between 1958 and 2005 forced by a linear increase of CO<sub>2</sub> (Hansen *et al.*, 1988). The model global mean temperature increases by 0.8°C, the vertically integrated specific humidity increases by 7% and the upper tropospheric specific humidity increases by 17% over this time interval (Table 12.1). Three-hourly output is sampled using the same orbit ground tracks, the monthly or seasonal mean values are computed, and the difference between 2005 and 1958 are formed. These sampled climate changes are compared to those obtained using the full model outputs.

An estimate of the magnitude of variations at scales smaller than the GCM grid is provided by observed correlation distances and the scatter of surface temperatures and lower troposphere humidities (Fig. 12.7). The rawinsonde data are from the lower 48 contiguous US states and include all monthly means from January 1978 through December 1982 (D. Gaffen, Ph.D. thesis - see Gaffen, 1992; Gaffen *et al.*, 1991, 1992). Correlations of monthly anomalies of 850 mb temperature and dewpoint (a good predictor of surface to 500 mb precipitable water - cf., Gaffen *et al.*, 1991; Liu *et al.*, 1991) as a function of the separation distance indicate that significant variations of these quantities (dashed lines indicate the 95% significance levels) occur at scales  $\geq 300$  km. Thus, the dominant variations of these variables are associated with synoptic scale motions which are almost resolved by the GCM grid. Smaller scale variation has been represented by bi-linear interpolations to each sample point between the GCM values at the grid box centers with added random noise. This approach overestimates the amplitude of smaller scale variations but also underestimates the correlations.

Figure 12.8 shows the effects of sampling on estimation of changes in June mean surface air temperature. Figure 12.8a shows the model predicted changes between 1958 and 2005 and Fig. 12.8b shows differences measured with Climsat sampling. Figure 12.8c shows the differences between Figs. 12.8a and 12.8b (sampling error), while Fig. 12.8d shows the sampling errors with cross-track scanning. Table 12.1 shows that the sampling errors for a non-scanning instrument are about 0.4°C rms, which produces an error in the global mean temperature of only 0.02°C. Both of these are several times smaller than the predicted changes. Figure 12.9 shows the geographic distribution of predicted June humidity changes and sampling errors for the upper troposphere. These results (Table 12.1) show that the Climsat sampling errors for non-scanning instruments are about 12% rms and only -1% for the global mean, significantly smaller than the predicted changes.

Figure 12.10a shows the GCM-predicted changes in summer zonal mean specific humidities as a function of latitude and pressure and Fig. 12.10b shows the changes estimated with Climsat sampling. Figures 12.10c and 12.10d show the absolute sampling errors and the relative sampling

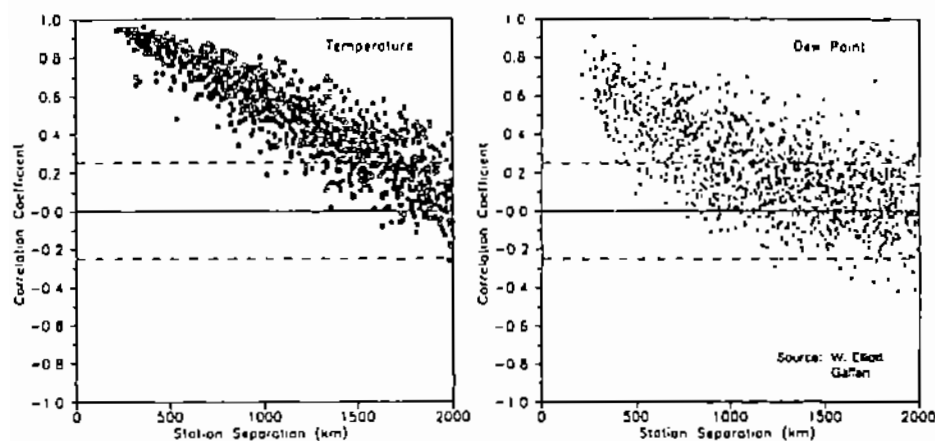


Fig. 12.7. Scatter diagrams of time record correlation coefficients for temperature and moisture against weather station separation distances.

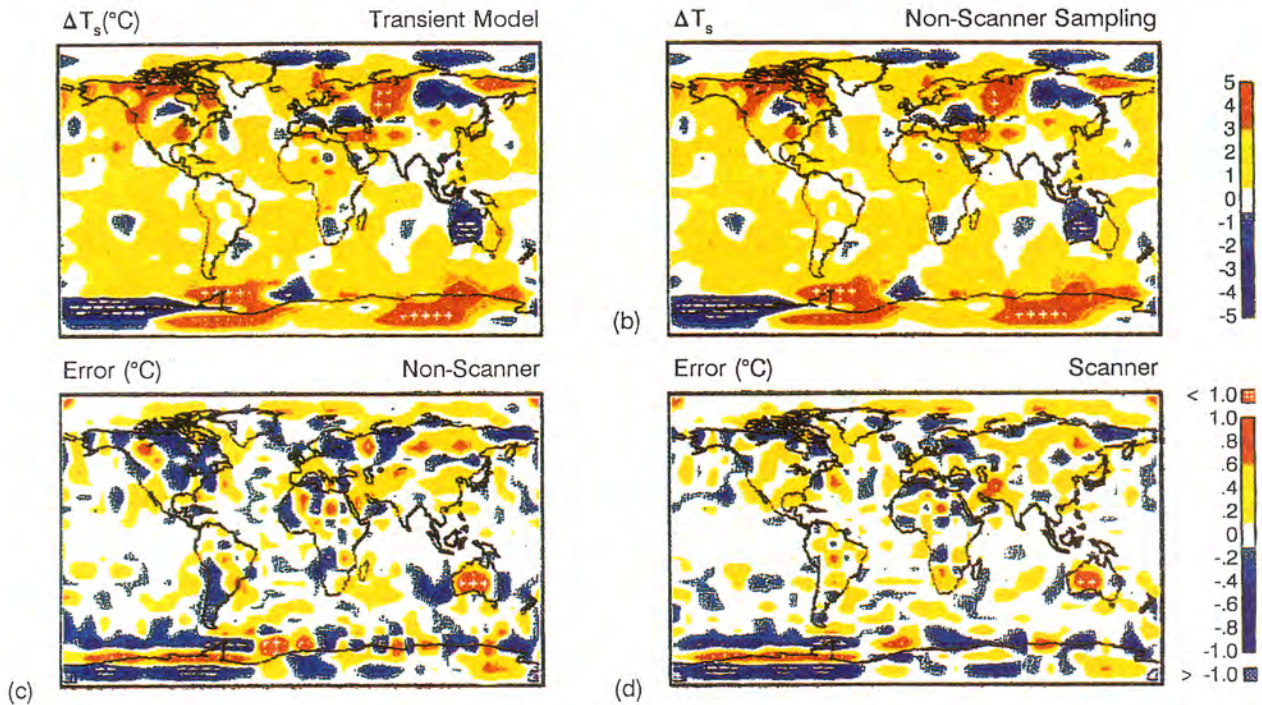
**TABLE 12.1.** Changes between summer 1958 and 2005 in globally averaged surface air temperature, vertically integrated and upper tropospheric specific humidities as predicted by the GISS GCM compared with sampling errors using a nadir-viewing instrument in Climsat orbits with and without cross-track scanning.

	<u>Global Mean Values</u>		<u>Root Mean Square</u>	
		(%)		(%)
<b>Climate Change</b>				
Surface Air Temperature (°C)	0.80	—	2.06	—
Vertically Integrated Specific Humidity (g/kg)	0.15	7.19	0.25	9.47
Upper Troposphere Specific Humidity (g/kg)	—	17.23	—	47.18
<b>Sampling Error (No Scanning)</b>				
Surface Air Temperature (°C)	0.02	—	0.43	—
Vertically Integrated Specific Humidity (g/kg)	0.003	0.001	0.03	1.33
Upper Troposphere Specific Humidity (g/kg)	—	-0.96	—	11.74
<b>Sampling Error (With Scanning)</b>				
Surface Air Temperature (°C)	0.02	—	0.36	—
Upper Troposphere Specific Humidity (g/kg)	—	-0.05	—	11.33

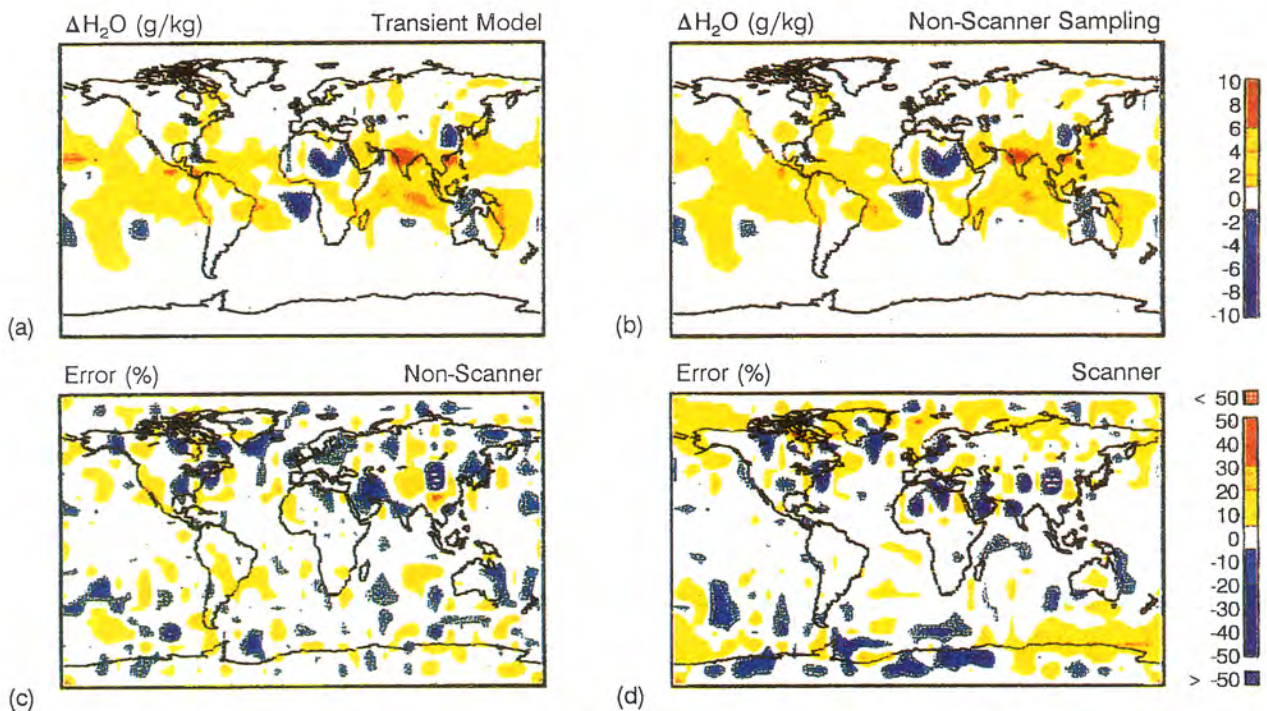
errors expressed as a percentage of the "true" climate change in Fig. 12.10a. The model predicted changes are largest in the upper troposphere and lower stratosphere and are about an order of magnitude larger than the sampling errors (cf., Table 12.1).

The counter-intuitive result that sampling with scanning instruments does not produce significantly smaller errors than with non-scanning instruments (Figs. 12.8 and 12.9, Table 12.1) focuses attention on the difficulty of detecting climate changes. The main problem is that the natural variability of climate parameters, even on interannual time scales, may be larger than the climate changes predicted to occur over a few decades (Hansen *et al.*, 1988; Manabe *et al.*, 1990; Lorenz, 1990; Karl *et al.*, 1991). Some of the interannual variability in datasets is, in fact, residual error caused by sampling of synoptic variations of the atmosphere and surface. Thus, the limit on measuring climate changes accurately is determined by the magnitude of these natural variations, which can be considered the intrinsic "noise". That this is the case with the sampling errors shown in Figs. 12.8 and 12.9 and Table 12.1 is revealed by three facts.

First, the spatial patterns of the climate changes, shown in Figs. 12.8a and 12.9a, are similar in character to the pattern of differences between any two Junes in the GCM control run (no climate change forcing). In a typical case, the rms regional differences in surface air temperature are about 3.2°C and in upper tropospheric humidity are about 37%, very similar to the rms regional differences in the climate change experiment (Table 12.1). The global mean differences are, however, much smaller in the control run comparison (e.g., 0.2°C for surface air temperature and 1-2% for upper



**Fig. 12.8.** Model-predicted changes (a) in monthly mean surface air temperature [(June 2005) – (June 1958)] and measured changes (b) with Climsat non-scanning sampling. Errors are shown as differences of (a) and (b) in (c). Differences produced by scanning sampling are shown in (d).



**Fig. 12.9.** Model-predicted changes (a) in specific humidity (g/kg) in the upper troposphere and measured changes (b) with Climsat non-scanning sampling. Errors are shown (in percent) for non-scanning sampling (c) and scanning sampling (d).



tropospheric humidity) than in the climate change comparison. Thus, the regional variability shown in Figs. 12.8a and 12.9a is predominately the consequence of different realizations of synoptic variations in any two months, rather than climate change. Moreover, changes in this regional variability between two months appear as differences in the global, monthly mean values of any parameter; in other words, this regional "noise" does not completely cancel in the global mean. Consequently, the global mean surface air temperature and upper tropospheric humidity changes are uncertain by at least 0.2°C and 1-2%, respectively, just because of natural variability.

Second, the sampling errors, shown in Figs. 12.8b and 12.9b, are proportional to the changes in Figs. 12.8a and 12.9a. This results from the fact that a one month time record of synoptic variability at one location actually represents only about 10-15 independent samples because the synoptic changes are correlated on time scales of a few days. Thus, for example, a single large storm event in a particular month will both increase the difference between monthly mean values and be more likely to increase the error in a sampled dataset because the storm is a "singular" event with low probability. This effect also explains why the natural variability in surface air temperature is a larger fraction of the climate change (about 25% of the global mean) than for upper tropospheric humidity (about 5% of the global mean), since the larger surface temperature variations occur at midlatitudes with longer correlation times (fewer samples) than the humidity variations which occur in the tropics with shorter correlation times (more samples).

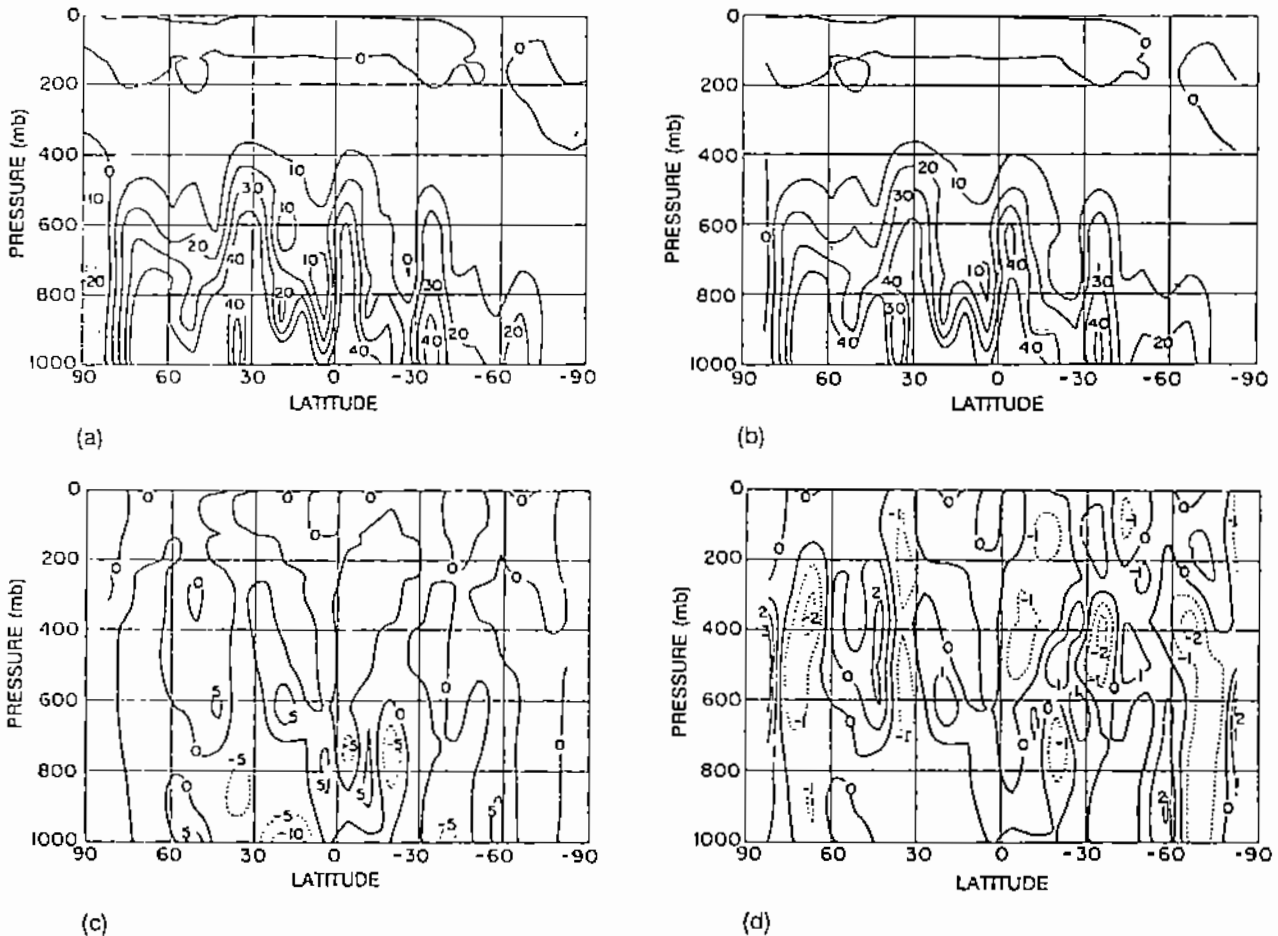


Fig. 12.10. Model-predicted zonal mean changes in specific humidity (a) the changes measured with Climsat non-scanning sampling (b) Absolute (c) and relative (d) differences are displayed in percent.

**TABLE 12.2. Summary of all sampling tests. Regional averages are from a 10° map grid.**

	Global Monthly <u>Average</u>	Global Seasonal <u>Average</u>	Regional Monthly <u>Average (rms)</u>
Surface temperature (°C)	< 0.2	< 0.1	< 0.5
Specific humidity errors (%) (vertical integrated) (upper troposphere)	< 0.1 < 2.0	< 0.1 < 1.0	< 2.0 < 12.0
Ozone column abundance (%)	< 0.03	< 0.02	< 2.0
Cloud top temperature (°C)	< 0.5	< 0.3	< 1.5
Cloud amount (%)	< 0.7	< 0.4	< 3.0

Third, the space-time distribution of the sampling from scanning instruments is different from that of non-scanning instruments, particularly at higher latitudes. The different distributions of the two sampling patterns interact with synoptic variations to produce about the same rms sampling errors but also cause differences in the measured global, monthly mean values of surface air temperature and upper tropospheric humidity that are as large as the differences between two months in the control run. In other words, these two sampling patterns can be considered as two different realizations of the natural variability, producing similar uncertainties in measured quantities. Thus, the much larger number of measurements made with the scanning instrument does not significantly reduce the sampling error which is already dominated by natural variability for the smaller non-scanning dataset.

These sampling studies confirm that the largest source of uncertainty in measuring climate change is limited sampling of natural (synoptic) variability, as long as the observing system provides complete and uniform global coverage and unbiased time sampling. (Even though the GCM tests assumed very large random measurement errors, the sample population for one month of data, even for non-scanning instruments, is so large as to nearly eliminate this source of uncertainty.) Since synoptic variations are correlated on time scales of a few days, the number of independent samples of these variations that can be obtained in one month (during which the forcing can be considered constant) is so small that the uncertainty in mean values remains much larger than predicted climate changes. Likewise, uncertainties in global mean values are not reduced by increasing the spatial resolution of observations because the synoptic variations are also correlated on large spatial scales (cf., Fig. 12.7), which places an intrinsic limit on the number of independent samples that can be obtained. These correlations explain why the non-scanning sampling from the Climatsat orbits is as good as the scanning sampling. Moreover, even if an observing system provides uniform space-time sampling, ordinary problems in operating instruments and computer systems cause data losses that produce gaps in spatial and temporal coverage that exaggerate the contribution of the intrinsic noise. Thus, the only way to reduce this source of sampling error enough to measure the predicted decadal climate changes is to make comparisons between observations averaged over at least 3-5 years in each of two decades.

Table 12.2 summarizes the results of the sampling studies using both data and GCM simulations by reporting the largest differences as upper limits on sampling errors. Comparison of these sampling errors with the accuracy requirements in Section 3 shows that Climatsat will generally be able to monitor plausible decadal changes of the forcings and feedbacks which it addresses (see also Section 7 and Table 7.4).

### 13. Panel Discussion

*Inez Fung, NASA Goddard Institute for Space Studies*

Dr. Manabe discussed a comprehensive strategy for the validation of a climate model. It includes the monitoring of the factors that force climate, the prediction of climate change by a state-of-the-art model and the validation of the model based upon the comparable assessment of predicted and observed climate changes (Fig. 13.1). He emphasized that the long-term monitoring of climate is an indispensable part of this strategy. In order to distinguish the anthropogenic change from the natural variation of climate, he also stressed the importance of studying the latter by use of a coupled ocean-atmosphere model.

With regard to the monitoring of the energy cycle, he suggested focussing our attention on the monitoring of those variables which we can measure with sufficient accuracy. Dr. Manabe noted specifically that, in the GFDL climate model calculation for doubled CO<sub>2</sub>, the CO<sub>2</sub>-induced changes of globally averaged, net radiative fluxes at the top of the atmosphere and horizontal transport of heat in the atmosphere and oceans are very small and probably beyond current measurement capabilities. Instead, it may be easier to monitor the long-term change in the thermal structure of the atmosphere and oceans. He suggested that radiation budget measurements are more appropriate as part of process studies, as opposed to continuous monitoring of the detection of long-term change. He noted, however, that it is essential for the validation of a climate model to monitor the long-term changes of key variables such as solar irradiances, cloud, snow cover, sea ice, aerosols and their radiative effect. *[Monitoring the radiation budget is still considered crucial, but since plans are well in hand for spacecraft missions for this purpose, we do not consider this as "missing" - Ed.]*

In conclusion, Dr. Manabe believes that Climsat is a prudent proposal that fills critical gaps in climate monitoring.

Dr. Wigley concurred with Dr. Manabe and emphasized that interpretation of the present climate record requires knowing also about the lag in realized climate warming due to the oceans. Thus complementary programs for frequent and regular monitoring of the 3-D structure of the ocean, such as proposed as part of the Global Climate Observing System (GCOS), can contribute. *[Earlier discussions mentioned also the potential contributions of acoustic tomography, such as proposed by Munk and Forbes (1989), for analysis of the ocean thermal lag problem. Climsat would also represent an important contribution to GCOS plans by providing better calibrated, though less detailed measurements to which the operational weather measurements could be anchored - Ed.]*

Dr. McElroy reviewed scientific questions about tropospheric ozone. He pointed out that in the past decade many of the surprising changes in ozone profiles in the lower stratosphere have been revealed by SAGE measurements. There are two issues concerning ozone profiles: (1) continued monitoring of the 3-D distribution of ozone changes and (2) understanding the mechanisms for the change. He agreed that proposed SAGE measurements on Climsat would be adequate for monitoring ozone changes in the lower stratosphere and upper troposphere. It would be better still if the monitoring could be extended down to 6-8 km in the troposphere. The monitoring must be done with an overview of stratospheric chemistry. Measurements of ozone concentrations need to be good to 3 ppm; CH<sub>4</sub> changes need to be measured as well. A strategy to understand the processes governing the ozone changes needs to be developed; it will most likely involve aircraft measurements in conjunction with the satellite measurements. *[Improvements of SAGE III over its predecessors will increase its depth of penetration into the troposphere (Section 8), but sampling questions remain and require study - Ed.]*

Dr. Charlson endorsed Climsat for monitoring aerosols to quantify their direct effects on the radiative balance of the planet. The science for the indirect effects of aerosols on clouds is relatively

## PREDICTION OF GLOBAL CLIMATE

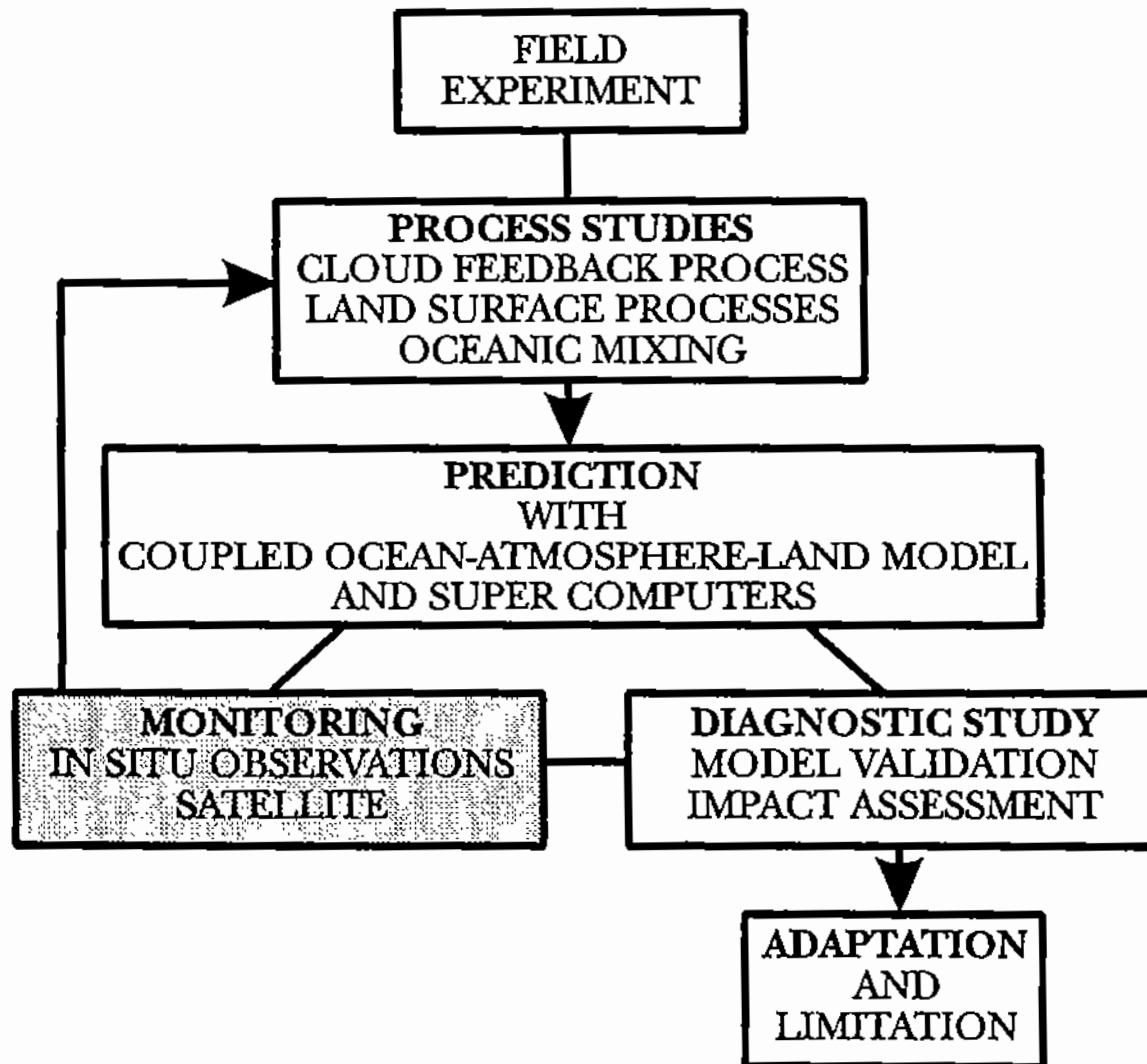


Fig. 13.1 Overall strategy for understanding and predicting climate change, as presented by S. Manabe.

young and it is premature to specify monitoring requirements to address that problem. Dr. Charlson also pointed out that there is a beautiful match between Climsat and ground-based programs, such as those of CMDL and AEROCE, in terms of geographic coverage and the sensitivity in optical thickness measured. However, the ground-based programs are not adequately funded at present. If adequately funded, they could provide the crucial ground-based supplement to Climsat. Echoing Dr. Manabe, he emphasized that understanding the role of aerosols in the changing climate comes only from the integration of ground-based and satellite datasets, process studies, documentation of aerosol composition and source fields in atmospheric chemistry models and climate models.

Dr. Hofmann reviewed the discussion on stratospheric aerosols and stressed the need for continued long-term monitoring of background aerosols in the lower stratosphere/upper troposphere. The monitoring is necessary because changes in background (without volcanic eruption) stratospheric aerosol can result directly from jet aircraft emissions or indirectly via changing stratospheric temperature and circulation. He also pointed out that increases in the mass of aerosols in the lower stratosphere have resulted from an increase in the number of large particles, even though the total number density has remained constant, so measurements of aerosol size are also needed. The relationship between changes in lower stratosphere ozone and large particle density is unclear and needs to be investigated.

Dr. Betts summarized the discussion on water vapor. He argued that the lack of a sufficiently accurate validation dataset of water vapor has been an important limitation on the improvement of climate models. Specifically, ground-based measurements of specific humidity remain poor above 6 km or below  $-40^{\circ}\text{C}$ ; the quality of humidity measurements from operational satellite instruments such as AMSU and HIRS in this region has not yet been established. Furthermore, products of data assimilation, such as the analyzed fields from ECMWF, are model dependent, and cannot be used as true tests of the performance of any climate model. It was only two years ago that variability in relative humidity at 300 mb in the tropics in the ECMWF GCM was validated by SAGE data, even though the SAGE data are biased towards clear sky.

Dr. Betts suggested that retrievals of humidity profiles need to resolve, at minimum, from the planetary boundary layer to the freezing level, from the freezing level to  $\sim 300$  mb, and above 300 mb. In other words, vertical resolution of a couple of kilometers is acceptable. *[Such resolution is readily achievable by the MINT instrument on Climsat, especially with cross-comparison to SAGE in the upper troposphere - Ed.]*

Dr. Betts concluded that Climsat can make an important contribution to a coupled dataset on thermodynamics and cloud structure. Because time scales are different at different heights in the atmosphere, this dataset will be crucial for understanding coupling on longer time scales in the tropics.

Dr. Wielicki presented his views on clouds. Monitoring requires instruments that are accurate enough to measure very small changes. He is doubtful that present instruments are capable of the level of accuracy needed for detecting changes in cloud properties. Process studies, on the other hand, will contribute to improving physics in models, which can then be used to extrapolate future changes. Dr. Wielicki believes that EOS has taken a visionary step towards obtaining measurements for understanding cloud processes. Nevertheless, lidar and radar measurements are not included and should be added in the future.

In the discussion opened to all workshop participants, there was a general consensus that decadal monitoring is crucial for understanding climate change and that the monitoring needs to be low cost so that it can be continued for decades. No expensive program will be maintained on decadal time scales. The monitoring should include both ground-based and satellite measurements. Calibration is a central issue. The urgent plea for a reference sonde network highlighted the

limitations of uncalibrated data for climate change studies. The discussions further emphasized Dr. Manabe's summary chart (Fig. 13.1) that the monitoring has to be carried out in the broader context of a program that also includes process studies and integrative modeling.

The discussions also generated many comments about EOS and about the relationship of Climsat to EOS.

Dr. Manabe asked whether the scientific objectives of EOS and other satellite programs have undergone the same careful scrutiny as Climsat has. He cautioned that if programs aim for more than what is absolutely needed, then inevitably scientific research will suffer during a budget crunch. He wanted to know: what are the scientific questions EOS is asking? what are the instruments needed to provide answers to the questions? and are those instruments included in EOS?

Dr. Wielicki replied that the evolution of EOS was different from that of Climsat. The Earth system is so intimately linked that it is not effective for each scientific discipline to separately address its measurement needs. The EOS strategy is to "combine and conquer" rather than to "divide and conquer." MODIS was mentioned as an example of an EOS instrument that serves the needs of several scientific disciplines.

Dr. Wielicki reiterated that EOS has recently undergone an engineering review. He also noted that the Payload and other EOS panels, comprising representatives from the science community, have spent innumerable days setting priorities for EOS.

Dr. Charlson emphasized that such reviews do not imply endorsement by the entire community, and he specifically pointed out that aerosol measurements had not been considered a priority by EOS until the recent Arizona meeting [*the EOS Tropospheric Anthropogenic Aerosol Workshop, December 16-17, 1991, chaired by R. Dickinson - Ed.*]. Dr. Hofmann commented that while ground-based measurements are acknowledged to be an integral part of EOS, and while members of that community were asked to assist in the justification of the program, there is as yet no follow-through (funding) to integrate ground-based measurements into EOS.

Dr. Manabe's sentiments were echoed several times throughout the discussion. It was suggested that the EOS program is too large for any scientist to fully grasp in its entirety, and that packaging global change observations on such a large scale effectively prohibits careful scrutiny, and thus there may indeed be gaps as well as unnecessary redundancy. Dr. McElroy suggested that there is room for programs intermediate between the regional detailed focus of ARM and the global all-encompassing ambitions of EOS.

It was pointed out that Climsat and EOS are synergistic as well as in competition. It is important to make clear how much duplication there is of Climsat on EOS. Climsat is clearly designed to be a monitoring mission. It was mentioned that the concept of monitoring may be somewhat different in the EOS program. A representative from NASA Headquarters (Dr. Ming-Ying Wei) said that while EOS has never been explicitly labelled as a monitoring program, it attempts to collect long-term datasets as best it can, but acknowledged that there may be data gaps.

Dr. Hansen explained that EOS can provide climate process data but does not fulfill the requirements of climate monitoring, showing a table listing reasons which are contained here in Table 7.5. First, EOS does not include an inclined precessing orbit, so that EOS is not able to monitor change of diurnal cycles. Second, EOS puts "many eggs in a large basket" which cannot be replaced easily, so that the failure of a single instrument or spacecraft will lead to a data gap. Third, monitoring for long-term change requires data continuity and instrument longevity for decades, which is a realistic possibility with Climsat. Fourth, Climsat is comprised of two satellites; the overlap allows cross-calibration of instruments on replacement satellites. EOS, by contrast, has back-

to-back missions with no "hot spares" (satellites to launch immediately after a failure). Fifth, small instruments on small satellites are inherently cheaper and easier to replace. Furthermore, EOS does not include all the instruments in the Climatsat proposal, in particular, the infrared interferometer, whose single detector gives the needed high wavelength-to-wavelength precision in the thermal region, and which has a proven long life. The conclusion is that Climatsat is needed as a complement to EOS.

Dr. Wielicki argued that EOS duplicates much of the capabilities of Climatsat, since both SAGE and EOSP are EOS selected instruments, and both AIRS on EOS and MINT proposed for Climatsat are spectrometers that cover the thermal region. *[Table 7.5 in Section 7 of this report explains why this apparent duplication of instrumentation does not mean duplication of climate monitoring capability. Neither SAGE nor EOSP is scheduled to fly until the 21st century, and then only on a single spacecraft and orbit. Additionally, the AIRS (infrared spectrometer) has been descoped and now measures only separate portions of the spectrum. If the Climatsat mission proceeds, SAGE and EOSP could be excluded from the EOS platforms, thus eliminating the potential duplication and reducing EOS costs - Ed.]* Dr. Rossow noted that instrument design should respond to the scientific questions posed. For example, even though several instruments claim to "do aerosols", most of them do not have the needed sensitivity to detect a change in optical thickness of even 0.1, not to mention the required 0.01.

The costs of EOS and Climatsat were also discussed. Dr. Mahlman compared the EOS budget of \$750M/yr to that of the US Global Change Research Program (USGCRP) at \$1.1B/yr. If we were starting over, the scientific community would "certainly not necessarily" spend the budget in the same way. It was pointed out that the USGCRP must address a large number of questions besides those addressed by EOS. Dr. Mahlman further observed that the wisdom of Climatsat is that it is designed specifically for monitoring and that its objectives and budget are consistent with the commitments of the USGCRP, whereas none of the EOS moneys is designated specifically for monitoring in support of the USGCRP.

Dr. Manabe cautioned that with a budget crunch, hardware is delayed while scientific research invariably is decimated. Dr. McElroy reminded the audience that budget crunches reduced the amount of effective science carried out in both the Apollo and Viking programs even though both programs had long-term interests in science.

Further conversation focused on the costs of Climatsat. Dr. Hansen stated that Climatsat instruments have well-proven predecessors and are not technological challenges, though they incorporate the latest technology where appropriate. With known weight and characteristics (e.g. the number of channels) of the instruments, cost estimates for each instrument should be fairly accurate. It was commented that the number of carbon copies of each instrument needs to be specified at the outset, so that exorbitant restart costs can be avoided, should the manufacturing plant be shut down, as in the case of SSM/I. How many copies are sufficient for two satellites to maintain data continuity should an instrument fail? Dr. Hansen said three for the initial 5-10 year period, but the number is dependent on actual lifetimes. *[Such a scenario presumes a common design target of 5-year instrument/spacecraft lifetime and one hot spare. Previous flight experience suggests that this is a reasonable estimate - Ed.]*

Dr. Hansen proposed that Climatsat data would be archived with EOSDIS, which has a protected budget. However, budgets for the essential complementary measurements and for scientific investigations using the data would depend on the scientific scope of and the number of scientists in the Climatsat program. Dr. Wielicki said that ERBE's science budget is \$5M/yr, which includes costs for data processing and quality checking. If ERBE is used as the model, then, with three instruments, the Climatsat science budget would amount to \$150M for a decade, comparable to the order of magnitude of the hardware costs. This, it was remarked, would be unprecedentedly heavy weighting towards science. Dr. Hansen cautioned against an expansion of Climatsat objectives, quoting Dr. V.

Suomi, who warned that "the worst enemy of a good experiment is a better experiment." The science and supplemental measurements of Climsat should be as tightly focused as possible.

There were comments that it is important to recognize that no satellite program is stand-alone. For example, the Dobson network is crucial to the calibration of TOMS data. Dr. Hofmann stressed that Climsat needs to lock in as much supplemental measurements in advance as possible. Several in-situ monitoring programs, such as those of CMDL and NDSC, all offer opportunities for comparison with and validation of Climsat data. Small programs, such as the balloon soundings of stratospheric water vapor using cross-wind hygrometers, should not be ignored. Sonde data, if calibrated, are crucial for all investigations of the hydrologic cycle, not just for validating water vapor retrievals by Climsat. Dr. Hansen suggested that perhaps some measurements could be funded as part of the Climsat program, while others could be leveraged into ongoing programs, as TRMM has led to increased funding for the Coupled Ocean-Atmosphere Research Experiment (COARE) of the Tropical Ocean/Global Atmosphere (TOGA) Program. Dr. Rind emphasized that satellite measurements should not be used as an excuse to "de-select" in-situ measurements.

The discussions adjourned at 3 p.m. Dr. Hansen thanked the participants for their valuable time and candid discussion. He stated that, because of their encouragement, he and his colleagues would continue to push for the Climsat concept.



## ACRONYMS

ACRIM:	Active Cavity Radiometer Irradiance Monitor
AEM:	Atmospheric Explorer Mission
AEROCE:	Air/Ocean Chemistry Experiment
AIRS:	Atmospheric Infrared Sounder (EOS instruments)
ARM:	Atmospheric Radiation Measurements (DOE program)
ATMOS:	Atmosphere and Ocean Satellite (German satellite program)
AVHRR:	Advanced Very High Resolution Radiometer (flown on NOAA satellites)
CCD:	Charge Coupled Device
CCN:	Cloud Condensation Nuclei
CFCs:	Chlorofluorocarbons
CERES:	Clouds and the Earth's Radiant Energy System (EOS instrument)
CMDL:	Climate Monitoring and Diagnostics Laboratory (NOAA)
DMS:	Dimethylsulphide
DMSP:	U.S. Defense Meteorological Satellite Program (operated by U.S. Air Force)
DOE:	U.S. Department of Energy
ECMWF:	European Center for Medium Range Weather Forecasts
EOS:	Earth Observing System
EOSP:	Earth Observing Scanning Polarimeter (EOS instrument)
ERBE:	Earth Radiation Budget Experiment
ERBS:	Earth Radiation Budget Satellite
GARP:	Global Atmospheric Research Program
GATE:	GARP Atlantic Tropical Experiment
GCM:	Global Climate Model or General Circulation Model
GCOS:	Global Climate Observing System
GFDL:	Geophysical Fluid Dynamics Laboratory (NOAA)
GISS:	Goddard Institute for Space Studies (NASA)
GOES:	Geostationary Operational Environmental Satellite (operated by NOAA)
HMGG:	Homogeneously Mixed Greenhouse Gases
IFOV:	Instantaneous Field of View
IPCC:	Intergovernmental Panel on Climate Change
IRIS:	Infrared Interferometer Spectrometer
ISCCP:	International Satellite Cloud Climatology Project
LIMS:	Limb Infrared Monitor of the Stratosphere
MINT:	Michelson Interferometer
MSE:	Mean Square Error
NASA:	U.S. National Aeronautics and Space Administration
NDSC:	Network for the Detection of Stratospheric Change
NOAA:	U.S. National Oceanic and Atmospheric Administration
OCPP:	Orbiter Cloud Photopolarimeter (flown on Pioneer Venus orbiter)
SAGE:	Stratospheric Aerosol and Gas Experiment (EOS instrument)
SAM:	Stratospheric Aerosol Measurement
SCARAB:	Scanner for Radiation Budget (French, Russian, German satellite series)
SMM:	Solar Maximum Mission
SOLSTICE:	Solar Stellar Irradiance Comparison Experiment
SSM/I:	Special Sensor Microwave/Imager (flown on DMSP satellites)
TES:	Thermal Emission Spectrometer
TOA:	Top of Atmosphere
TOMS:	Total Ozone Mapping Spectrometer
TOVS:	TIROS Operational Vertical Sounder
TRMM:	Tropical Rainfall Measuring Mission (Japan-U.S. satellite mission)
UARS:	Upper Atmospheric Research Satellite
USGCRP:	United States Global Change Program
VAS:	VISSR Atmospheric Sounder (flown on GOES satellites)
VISSR:	Visible and Infrared Spin-Scan Radiometer (flown on many geostationary weather satellites)
WCRP:	World Climate Research Program
WMO:	World Meteorological Organization
WOCE:	World Ocean Circulation Experiment

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## REFERENCES

- Ackerman, T.P., 1979: On the effect of CO<sub>2</sub> on atmospheric heating rates. *Tellus*, **31**, 115-123.
- Albrecht, B.A., 1989: Aerosols, cloud microphysics, and fractional cloudiness. *Science*, **245**, 1227-1230.
- Ardanuy, P.E., H.L. Kyle, and D. Hoyt, 1992: Global relationships among the earth's radiation budget, cloudiness, volcanic aerosols, and surface temperature. *J. Climate*, **5**, 1120-1139.
- Arking, A., 1993: Water vapor and lapse rate feedback: Insight from a one-dimensional climate model. *J. Climate*, (submitted).
- Baggeroer, A., and W. Munk, 1992: The Heard Island feasibility test. *Phys. Today*, **45**, 22-30.
- Barnett, T.P., 1991: The interaction of multiple time-scales in the tropical climate system. *J. Climate*, **4**, 269-285.
- Barnett, T.P., A.D. DelGenio, and R.A. Ruedy, 1992: Unforced decadal fluctuations in a coupled model of the atmosphere and ocean mixed layer. *J. Geophys. Res.*, **97**, 7341-7354.
- Bates, T.S., R.J. Charlson, and R.H. Gammon, 1987: Evidence for the climatic role of marine biogenic sulfur. *Nature*, **329**, 319-321.
- Bell, T.L., 1987: A space-time stochastic model of rainfall for satellite remote-sensing studies. *J. Geophys. Res.*, **92**, 9631-9643.
- Bell, T.L., and N. Reid, 1993: Detection of the diurnal cycle of tropical rainfall from satellite observations. *J. Appl. Meteor.*, (in press).
- Bell, T.L., A. Abdullah, R.L. Martin, and G.R. North, 1990: Sampling errors for satellite-derived tropical rainfall: Monte Carlo study using a space-time stochastic model. *J. Geophys. Res.*, **95**, 2195-2206.
- Betts, A.K., 1991: Global warming and the tropical water budget. Testimony to the United States Senate Commerce Committee, October 7, Washington, D.C.
- Betts, A.K., and Harshvardhan, 1987: Thermodynamic constraint on the cloud liquid water feedback in climate models. *J. Geophys. Res.*, **92**, 8483-8485.
- Brest, C.L., and W.B. Rossow, 1992: Radiometric calibration and monitoring of NOAA AVHRR data for ISCCP. *Int. J. Remote Sensing*, **13**, 235-273.
- Broecker, W.S., 1987: The biggest chill. *Nat. Hist.*, **96**, 74-82.
- Brooks, D.R., E.F. Harrison, P. Minnis, J.T. Suttles, and R.S. Kandel, 1986: Development of algorithms for understanding the temporal and spatial variability of the Earth's radiation balance. *Rev. Geophys.*, **24**, 422-438.
- Carlson, B.E., A.A. Lacis, and W.B. Rossow, 1992a: The abundance and distribution of water vapor in the Jovian troposphere as inferred from Voyager IRIS observations. *Astrophys. J.*, **388**, 648-668.
- Carlson, B.E., A.A. Lacis, and W.B. Rossow, 1992b: Ortho-para-hydrogen equilibrium on Jupiter. *Astrophys. J.*, **393**, 357-372.

- Cess, R.D., and 19 co-authors, 1989: Interpretation of cloud-climate feedback as produced by 14 atmospheric general circulation models. *Science*, **245**, 513-516.
- Cess, R.D., and 31 co-authors, 1990: Intercomparison and interpretation of climate feedback processes in nineteen atmospheric general circulation models. *J. Geophys. Res.*, **95**, 16,601-16,615.
- Cess, R.D., and 32 co-authors, 1991: Interpretation of snow-climate feedback as produced by 17 general circulation models. *Science*, **253**, 888-892.
- Chahine, M.T., 1974: Remote sounding of cloudy atmospheres. I. The single cloud layer. *J. Atmos. Sci.*, **31**, 233-243.
- Chandra, S., 1991: The solar UV related changes in total ozone from a solar rotation to a solar cycle. *Geophys. Res. Lett.*, **18**, 837-840.
- Charlson, R.J., J. Langner, and H. Rodhe, 1990: Sulfate aerosols and climate. *Nature*, **348**, 22-26.
- Charlson, R.J., J. Langner, H. Rodhe, C.B. Leovy, and S.G. Warren, 1991: Perturbation of the northern hemisphere radiative balance by backscattering from anthropogenic sulfate aerosols. *Tellus*, **43AB**, 152-163.
- Charlson, R.J., S.E. Schwartz, J.M. Hales, R.D. Cess, J.A. Coakley, J.E. Hansen, and D.J. Hofmann, 1992: Climate Forcing by anthropogenic aerosols. *Science*, **255**, 423-430.
- Christensen, P.R., D.L. Anderson, S.C. Chase, R.N. Clark, H.H. Kieffer, M.C. Malin, J.C. Pearl, J. Carpenter, N. Bandiera, F.G. Brown, and S. Silverman, 1992: Thermal emission spectrometer experiment: Mars Observer Mission. *J. Geophys. Res.*, **97**, 7719-7734.
- Clough, S.A., F.X. Kneizys, and R.W. Davies, 1989a: Line shape and the water vapor continuum. In, *Proceedings of the International Radiation Symposium*. Eds. J. Lenoble and J-F. Geleyn, Deepak Publishing, Hampton, VA, pp. 355-359.
- Clough, S.A., R.D. Worsham, W.L. Smith, H.E. Revercomb, R.O. Knuteson, H.W. Woolf, G.P. Anderson, M.L. Hoke, and F.X. Kneizys, 1989b: Validation of FASCODE calculations with HIS spectral radiance measurements. In, *IRS '88: Current Problems in Atmospheric Radiation*. Eds. J. Lenoble and J. F. Geleyn, Deepak Publishing, Hampton, Va., pp. 376-379.
- Coakley, J.A., and R.D. Cess, 1985: Response of the NCAR community climate model to the radiative forcing of naturally occurring tropospheric aerosol. *J. Atmos. Sci.*, **42**, 1677-1692.
- Coakley, J.A., R.L. Bernstein, and P.A. Durkee, 1987: Effect of ship-stack effluents on cloud reflectivity. *Science*, **237**, 1020-1022.
- Coffeen, D.L., and J.E. Hansen, 1972: Airborne infrared polarimetry. In, *Proceedings, Eighth International Symposium on the Remote Sensing of the Environment*, 515-522.
- Coffeen, D.L., and J.E. Hansen, 1974: Polarization studies of planetary atmospheres. In, *Planets, Stars and Nebulae*. Eds. Univ. Arizona Press, Tucson, 1133 pp.
- Conrath, B.J., R.A. Hanel, V.G. Kunde, and C. Prabhakara, 1970: The infrared interferometer experiment on Nimbus 3. *J. Geophys. Res.*, **75**, 5831-5857.
- Conrath, B., D. Gautier, R. Hanel, G. Lindal, and A. Marten, 1987: The helium abundance of Uranus from Voyager measurements. *J. Geophys. Res.*, **92**, 15003-15010.

- Conrath, B., F.M. Flasar, R. Hanel, V. Kunde, M. Maguire, J. Pearl, J. Pirraglia, R. Samuelson, P. Gierasch, A. Weir, B. Bevard, D. Gautier, D. Cruikshank, L. Horn, R. Springer, and W. Shaffer, 1989: Infrared observations of the Neptunian system. *Science*, **246**, 1454-1459.
- Cunnold, D.M., W.P. Chu, R.A. Barnes, M.P. McCormick, and R.E. Veiga, 1989a: Validation of SAGE II ozone measurements. *J. Geophys. Res.*, **94**, 8447-8460.
- Cunnold, D.M., W.P. Chu, R.A. Barnes, M.P. McCormick, and R.E. Veiga, 1989b: Validation of SAGE II NO<sub>2</sub> measurements. *J. Geophys. Res.*, **96**, 12,913-12,925.
- D'Almeida, G., 1987: On the variability of desert aerosol radiative characteristics. *J. Geophys. Res.*, **92**, 3017-3026.
- DelGenio, A.D., 1993: Convective and large-scale cloud processes in global climate models. In, *Energy and Water Cycles in the Climate System*. Eds. Proceedings, NATO Advanced Study Institute, Sept. 30 - Oct. 11, 1991, Glucksburg, Germany.
- DelGenio, A.D., A.A. Lacis, and R.A. Ruedy, 1991: Simulations of the effect of a warmer climate on atmospheric humidity. *Nature*, **251**, 382-385.
- Dickinson, R.E., and R.J. Cicerone, 1986: Future global warming from atmospheric trace gases. *Nature*, **319**, 109-115.
- Dulac, F., D. Tanre, G. Bergametti, P. Bua-Menard, M. Desbois, and D. Sutton, 1992: Assessment of the African airborne dust mass over the western Mediterranean sea using Meteosat data. *J. Geophys. Res.*, **97**, 2489-2506.
- Eddy, J.A., 1976: The Maunder minimum. *Science*, **192**, 1189-1202.
- Ellsaesser, H.W., 1983: Stratospheric water vapor. *J. Geophys. Res.*, **88**, 3897-3906.
- Farman, J.C., B.G. Gardiner, and J.D. Shanklin, 1985: Large losses of ozone in Antarctica reveal seasonal ClO<sub>x</sub>/NO<sub>x</sub> interaction. *Nature*, **315**, 207-210.
- Foley, J.A., K.E. Taylor, and S.J. Ghan, 1991: Planktonic dimethylsulfide and cloud albedo: An estimate of the feedback response. *Climatic Change*, **18**, 1-15.
- Fouquart, Y., B. Bonnel, M. Chaoui Roquai, and R. Santer, 1987: Observations of Saharan aerosols: results of ECLATS field experiment. Part I. Optical thickness and aerosol size distributions. *J. Clim. Appl. Meteorol.*, **26**, 28-37.
- Friis-Christensen, E., and K. Lassen, 1991: Length of the solar cycle: an indicator of solar activity closely associated with climate. *Science*, **254**, 698-700.
- Gaffen, D.J., 1992: Observed annual and interannual variations in tropospheric water vapor. *NOAA Tech. Memo. ERL ARL-198*, 162 pp.
- Gaffen, D.J., T.P. Barnett, and W.P. Elliott, 1991: Space and time scales of global tropospheric moisture. *J. Climate*, **4**, 989-1008.
- Gaffen, D.J., A. Robock, and W.R. Elliott, 1992: Annual cycle of tropospheric water vapor. *J. Geophys. Res.*, **97**, 18,185-18,193.
- Gutzler, D.S., 1992: Climatic variability of temperature and humidity over the tropical western Pacific. *J. Geophys. Res.*, **19**, 1595-1598.



- Han, Q., 1992: *Global survey of effective particle size in liquid water clouds*. Ph.D. dissertation, Columbia., 200 pp.
- Hanel, R.A., B. Schlachman, F.D. Clark, C.H. Prokesh, J.B. Taylor, W.M. Wilson, and L. Chaney, 1970: The Nimbus 3 Michelson interferometer. *Appl. Opt.*, **9**, 1767-1774.
- Hanel, R.A., B.J. Conrath, V.G. Kunde, C. Prabhakara, I. Revah, V.V. Salomonson, and G. Wolford, 1972a: The Nimbus 4 infrared spectroscopy experiment I. Calibrated thermal emission spectra. *J. Geophys. Res.*, **77**, 2629-2641.
- Hanel, R., B. Conrath, W. Hovis, V. Kunde, P. Lowman, W. Maguire, J. Pearl, J. Pirraglia, C. Prabhakara, and B. Schlachman, 1972b: Investigation of the Martian environment by infrared spectroscopy on Mariner 9. *Icarus*, **17**, 423-442.
- Hanel, R., D. Crosby, L. Herath, D. Vanous, D. Collins, H. Creswick, C. Harris, and M. Rhodes, 1980: Infrared spectrometer for Voyager. *Appl. Opt.*, **19**, 1391-1400.
- Hanel, R.A., B.J. Conrath, L.W. Herath, V.G. Kunde, and J.A. Pirraglia, 1981: Albedo, internal heat, and energy balance of Jupiter: Preliminary results of the Voyager infrared investigation. *J. Geophys. Res.*, **86**, 8705-8712.
- Hanel, R.A., B.J. Conrath, V.G. Kunde, J.C. Pearl, and J.A. Pirraglia, 1983: Albedo, internal heat flux, and energy balance of Saturn. *Icarus*, **53**, 262-285.
- Hanel, R., B. Conrath, F.M. Flasar, V. Kunde, W. Maguire, J. Pearl, J. Pirraglia, R. Samuelson, D. Cruikshank, D. Gautier, P. Gierasch, L. Horn, and P. Schulte, 1986: Infrared observations of the Uranian system. *Science*, **233**, 70-74.
- Hansen, J., 1991: Can the climate be engineered? Invited talk at Amer. Geophys. Union, San Francisco, December 9.
- Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, G. Russell, and P. Stone, 1988: Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. *J. Geophys. Res.*, **93**, 9341-9364.
- Hansen, J., A. Lacis, and M. Prather, 1989: Greenhouse effect of chlorofluorocarbons and other trace gases. *J. Geophys. Res.*, **94**, 16,417-16,421.
- Hansen, J., A. Lacis, D. Rind, R. Ruedy, M. Sato, and H. Wilson, 1993: Global climate change. *Res. Explor.* (in press).
- Hansen, J., A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy, and J. Lerner, 1984: Climate sensitivity: analysis of feedback mechanisms. In, *Climate Processes and Climate Sensitivity*. Eds. J. E. Hansen and T. Takahashi, Geophys. Monogr. Ser. 29, AGU, Washington, D.C., 130-163.
- Hansen, J., and S. Lebedeff, 1987: Global trends of measured surface air temperature. *J. Geophys. Res.*, **92**, 13,345-13,372.
- Hansen, J., W. Rossow, and I. Fung, 1990: The missing data on global climate change. *Issues Sci. Tech.*, **7**, 62-69.
- Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy, and L. Travis, 1983: Efficient three-dimensional global models for climate studies: models I and II. *Mon. Wea. Rev.*, **111**, 609-662.

- Hansen, J.E., 1971: Multiple scattering of polarized light in planetary atmospheres. II. Sunlight reflected by terrestrial water clouds. *J. Atmos. Sci.*, **28**, 1400-1426.
- Hansen, J.E., and A. Arking, 1971: Clouds of Venus: Evidence for their nature. *Science*, **171**, 669-672.
- Hansen, J.E., and J.W. Hovenier, 1974: Interpretation of the polarization of Venus. *J. Atmos. Sci.*, **31**, 1137-1160.
- Hansen, J.E., A. Lacis, R. Ruedy, and M. Sato, 1992: Potential climate impact of Mount Pinatubo eruption. *Geophys. Res. Lett.*, **19**, 215-218.
- Hansen, J.E., and A.A. Lacis, 1990: Sun and dust versus greenhouse gases: an assessment of their relative roles in global climate change. *Nature*, **346**, 713-719.
- Hansen, J.E., and J.B. Pollack, 1970: Near-infrared light scattering by terrestrial clouds. *J. Atmos. Sci.*, **27**, 265-281.
- Hansen, J.E., and L.D. Travis, 1974: Light scattering in planetary atmospheres. *Space Sci. Rev.*, **16**, 527-610.
- Harrison, E.F., P. Minnis, and G.G. Gibson, 1983: Orbital and cloud cover sampling analyses for multisatellite earth radiation budget experiments. *J. Spacecraft Rockets*, **20**, 441-445.
- Henderson-Sellers, A., 1986: Increasing clouds in a warming world. *Climatic Change*, **9**, 267-309.
- Henderson-Sellers, A., 1989: North American total cloud amount variations in this century. *Global Plan. Change*, **1**, 175-194.
- Hofmann, D.J., 1990: Increase in the stratospheric background sulfuric acid aerosol mass in the past 10 years. *Science*, **248**, 996-1000.
- Hoyt, D.V., H.L. Kyle, J.R. Hickey, and R.H. Maschhoff, 1992: The Nimbus-7 solar total irradiance: a new algorithm for its derivation. *J. Geophys. Res.*, **97**, 51-63.
- IPCC (Intergovernmental Panel on Climate Change), 1990: Climate Change. In, *WMO/UNEP*. Eds. J. T. Houghton, G. J. Jenkins and J. J. Ephraums, Cambridge (U.K.), Cambridge University Press, 365 pp.
- IPCC (Intergovernmental Panel on Climate Change), and S.K. Varney, 1992: Climate Change 1992. In, *The Supplementary Report to the IPCC Scientific Assessment*. Eds. J. T. Houghton and B. A. Callander, Cambridge University Press, 200 pp.
- Jacquemoud, S., and F. Baret, 1990: PROSPECT: A model of leaf optical properties spectra. *Remote Sens. Environ.*, **34**, 75-91.
- Jankowiak, I., and D. Tanre, 1992: Satellite climatology of Saharan dust outbreaks: Method and preliminary results. *J. Climate*, **5**, 646-656.
- Jensen, E.J., and O.B. Toon, 1992: The potential effects of volcanic aerosols on cirrus cloud microphysics. *Geophys. Res. Lett.*, **19**, 1759-1762.
- Jones, P.D., T.M.L. Wigley, and P.B. Wright, 1986: Global temperature variations between 1861 and 1984. *Nature*, **322**, 430-434.

- Joseph, J.H., 1984: The sensitivity of a numerical model of the global atmosphere to the presence of desert aerosol. In, *Aerosols and their Climatic Effects*. Eds. H. E. Gerber and A. Deepak, Deepak Publ., pp. 215-226.
- Kandel, R., 1990: Satellite observation of the Earth radiation budget and clouds. *Space Sci. Rev.*, **52**, 1-32.
- Karl, T.R., and P.M. Steurer, 1990: Increased cloudiness in the United States during the first half of the twentieth century. *Geophys. Res. Lett.*, **17**, 1925-1928.
- Karl, T.R., R.R. Heim, and R.G. Quayle, 1991: The greenhouse effect in central North America: If not now, when? *Science*, **251**, 1058-1061.
- Karl, T.R., R.W. Knight, and J.R. Christy, 1993: Global and hemispheric temperature trends: uncertainties related to inadequate spatial sampling. *J. Climate*, (submitted).
- Kaufman, Y.J., R.S. Fraser, and R.L. Mahoney, 1991: Fossil fuel and biomass burning effect on climate - heating or cooling? *J. Climate*, **4**, 578-588.
- Kawabata, K., D.L. Coffeen, J.E. Hansen, W.A. Lane, M. Sato, and L.D. Travis, 1980: Cloud and haze properties from Pioneer Venus polarimetry. *J. Geophys. Res.*, **85**, 8129-8140.
- Kedem, B., L. Chiu, and G.R. North, 1990: Estimation of mean rainrate: Application to satellite observations. *J. Geophys. Res.*, **95**, 1965-1972.
- Kunde, V.G., B.J. Conrath, R.A. Hanel, W.C. Maguire, C. Prabhakara, and V.V. Salomonson, 1974: The Nimbus-4 Infrared Spectroscopy Experiment, 2. Comparison of observed and theoretical radiances from 425-1450  $\text{cm}^{-1}$ . *J. Geophys. Res.*, **79**, 777-784.
- Kunde, V., R. Hanel, W. Maguire, D. Gautier, J.P. Baluteau, A. Marten, A. Chedin, N. Husson, and N. Scott, 1982: The tropospheric gas composition of Jupiter's North Equatorial Belt ( $\text{NH}_3$ ,  $\text{PH}_3$ ,  $\text{CH}_3\text{D}$ ,  $\text{GeH}_4$ ,  $\text{H}_2$ ) and the Jovian D/H isotopic ratio. *Astrophys. J.*, **263**, 443-467.
- Kurylo, M.J., and S. Solomon, 1990: *Network for the Detection of Stratospheric Change: A Status and Implementation Report*. NASA/NOAA Joint Report, Code EEU, NASA Headquarters, NOAA Aeronomy Laboratory, Boulder, 71 pp.
- Lacis, A.A., D.J. Wuebbles, and J.A. Logan, 1990: Radiative forcing of climate by changes of the vertical distribution of ozone. *J. Geophys. Res.*, **95**, 9971-9981.
- Lacis, A., J. Hansen, and M. Sato, 1992: Climate forcing by stratospheric aerosols. *Geophys. Res. Lett.*, **19**, 1607-1610.
- Laing, A., and J.M. Fritsch, 1992: Mesoscale convective complexes in Africa and the Indian subcontinent. In, *Preprints of the 11th International Conference on Clouds and Precipitation*. Eds. Montreal, 17-21 August 1992.
- Lamb, H.H., 1970: Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance. *Phil. Trans. Roy. Soc., London*, **A266**, 424-533.
- Larson, J., et al., 1993: A comparison of the SAGE II tropospheric water vapor to radiosonde measurements. *J. Geophys. Res.* (in press).
- Laughlin, C., 1981: On the effect of temporal sampling on the observation of mean rainfall. In, *Precipitation Measurements from Space*. Eds. D. Atlas and O. Thiele, Workshop Report, NASA Goddard Space Flight Center, Greenbelt, Md., pp. D59-D66.

- Le Texier, H., S. Solomon, and R.R. Garcia, 1988: The role of molecular hydrogen and methane oxidation in the water vapour budget of the stratosphere. *Quart. J. Roy. Met. Soc.*, 114, 281-295.
- Lean, J., 1991: Variations in the sun's radiative output. *Rev. Geophys.*, 29, 505-535.
- Lean, J., A. Skumanich, and O. White, 1992: Estimating the sun's radiative output during the Maunder minimum. *J. Geophys. Res.*, 19, 1591-1594.
- Lindzen, R.S., 1990: Some coolness concerning global warming. *Bull. Amer. Meteorol. Soc.*, 71, 288-299.
- Liou, K.N., S.C. Ou, Y. Takano, F.P.J. Valero, and T.P. Ackerman, 1990: Remote sounding of the tropical cirrus cloud temperature and optical depth using 6.5 and 10.5  $\mu\text{m}$  radiometers during STEP. *J. Appl. Meteor.*, 29, 716-726.
- Liu, W.T., W. Tang, and P.P. Niiler, 1991: Humidity profiles over the ocean. *J. Climate*, 4, 1023-1034.
- Lorenz, E., 1963: Deterministic non-periodic flow. *J. Atmos. Sci.*, 20, 130-141.
- Lorenz, E.N., 1990: Can chaos and intransitivity lead to interannual variability? *Tellus*, 42A, 378-389.
- Manabe, S., K. Bryan, and M.J. Spelman, 1990: Transient response of a global ocean-atmosphere model to a doubling of atmospheric carbon dioxide. *J. Phys. Oceanogr.*, 20, 722-749.
- McConnell, A., and G.R. North, 1987: Sampling errors in satellite estimates of tropical rain. *J. Geophys. Res.*, 92, 9567-9570.
- McCormick, M.P., P. Hamill, T.J. Pepin, W.P. Chu, T.J. Swissler, and L.R. McMaster, 1979: Satellite studies of the stratospheric aerosol. *Bull. Amer. Meteorol. Soc.*, 60, 1038-1046.
- McCormick, M.P., R.E. Veiga, and W.P. Chu, 1992: Stratospheric ozone profile and total ozone trends derived from the SAGE I and SAGE II data. *Geophys. Res. Lett.*, 19, 269-272.
- Miller, D., and J.M. Fritsch, 1991: Mesoscale convective complexes in the western Pacific region. *Mon. Wea. Rev.*, 119, 2978-2292.
- Mishchenko, M.I., 1991a: Reflection of polarized light by plane-parallel slabs containing randomly-oriented, nonspherical particles. *JQSRT*, 46, 171-181.
- Mishchenko, M.I., 1991b: Light scattering by randomly oriented axially symmetric particles. *J. Opt. Soc. Am. A.*, 8, 871-882.
- Molnar, G., and W.C. Wang, 1992: Effects of cloud optical property feedbacks on the greenhouse warming. *J. Climate*, 5, 814-821.
- Mount, G.H., R.W. Sanders, A.C. Schmeltekopf, and S. Solomon, 1987: Visible spectroscopy at McMurdo Station Antarctica, 1, Overview and daily variations of  $\text{NO}_2$  and  $\text{O}_3$ , Austral spring, 1986. *J. Geophys. Res.*, 92, 8320-8328.
- Munk, W.H., and A.M.G. Forbes, 1989: Global ocean warming: an acoustic measure? *J. Phys. Oceanogr.*, 19, 1765-1778.

- Nakajima, T., and M.K. King, 1990: Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. Part I: Theory. *J. Atmos. Sci.*, **47**, 1878-1893.
- North, G.R., and S. Nakamoto, 1989: Formalism for comparing rain estimation designs. *J. Atmos. Oceanic Technol.*, **6**, 985-992.
- Oort, A.H., 1978: Adequacy of the rawinsonde network for global circulation studies tested through numerical model output. *Mon. Wea. Rev.*, **106**, 174-195.
- Osborn, M.T., J.M. Rosen, M.P. McCormick, P.-H. Wang, J.M. Livingston, and T.J. Swissler, 1989: SAGE II aerosol correlative observations: profile measurements. *J. Geophys. Res.*, **94**, 8353-8366.
- Patterson, E.M., D.A. Gillette, and B.H. Stockton, 1977: Complex index of refraction between 300 and 700 nm for Saharan aerosols. *J. Geophys. Res.*, **82**, 3153-3160.
- Peixoto, J.P., and A.H. Oort, 1992: *Physics of Climate*. American Institute of Physics, New York, 520 pp.
- Penner, J.E., R.E. Dickinson, and C.A. O'Neill, 1992: Effects of aerosol from biomass burning on the global radiation budget. *Science*, **256**, 1432-1434.
- Platt, C.M.R., and Harshvardhan, 1988: Temperature dependence of cirrus extinction: Implications for climate feedback. *J. Geophys. Res.*, **93**, 11,051-11,058.
- Potter, G.L., H.W. Eilsaesser, M.C. MacCracken, and J.S. Ellis, 1981: Albedo change by man: test of climatic effects. *Nature*, **291**, 47-49.
- Prabhakara, C., R.S. Fraser, G. Dalu, M.-L. Wu, and R.J. Curran, 1988: Thin cirrus clouds: Seasonal distribution over oceans deduced from Nimbus-4 IRIS. *J. Appl. Meteor.*, **27**, 379-399.
- Prabhakara, C., J.-M. Yoo, G. Dalu, and R.S. Fraser, 1990: Deep optically thin cirrus clouds in the polar regions. Part I. Infrared Extinction Characteristics. *J. Appl. Meteor.*, **29**, 1313-1329.
- Prinn, R.G., 1988: Toward an improved global network for determination of tropospheric ozone climatology trends. *J. Atmos. Chem.*, **6**, 281-298.
- Prospero, J.M., R.A. Glaccum, and R.T. Ness, 1981: Atmospheric transport of soil dust from Africa to South America. *Nature*, **289**, 570-572.
- Radke, L.F., J.A. Coakley, and M.D. King, 1989: Direct and remote sensing observations of the effects of ships on clouds. *Science*, **246**, 1146-1149.
- Ramanathan, V., R.J. Cicerone, H.B. Singh, and J.T. Kiehl, 1985: Trace gas trends and their potential role in climate change. *J. Geophys. Res.*, **90**, 5547-5557.
- Ramaswamy, V., M.D. Schwarzkopf, and K.P. Shine, 1992: Radiative forcing of climate from halocarbon-induced stratospheric ozone loss. *Nature*, **355**, 810-812.
- Rao, C.R.N., L.L. Stowe, E.P. McClain, J. Sapper, and M.P. McCormick, 1988: Development and application of aerosol remote sensing with AVHRR data from the NOAA satellites. In, *Aerosols and Climate*. Eds. P. V. Hobbs, Hampton, Va., A. Deepak Publ., 486 pp.
- Raval, A., and V. Ramanathan, 1989: Observational determination of the greenhouse effect. *Nature*, **342**, 758-761.

- Reber, C.A., 1990: The upper atmosphere research satellite. *Eos*, 71, 1867-1868, 1873-1874, 1878.
- Reinsel, G.C., G.C. Tiao, J.J. DeLuisi, C.L. Mateer, A.J. Miller, and J.E. Frederick, 1984: Analysis of upper stratospheric Umkehr ozone profile data for trends and the effect of stratospheric aerosols. *J. Geophys. Res.*, 89, 4833-4840.
- Rind, D., E.W. Chiou, W. Chu, J. Larsen, S. Oltmans, J. Lerner, M.P. McCormick, and L. McMaster, 1991: Positive water vapor feedback in climate models confirmed by satellite data. *Nature*, 349, 500-503.
- Rind, D., E.W. Chiou, W. Chu, S. Oltmans, J. Lerner, J. Larsen, M.P. McCormick, and L. McMaster, 1993: Overview of the SAGE II water vapor observations: methods, validation and data characteristics. *J. Geophys. Res.*, 98, (in press).
- Rossow, W.B., and L.C. Garder, 1993: Validation of ISCCP cloud detection. *J. Climate*. (in press).
- Rossow, W.B., and R.A. Schiffer, 1991: ISCCP cloud data products. *Bull. Amer. Meteor. Soc.*, 72, 2-20.
- Rossow, W.B., L.C. Garder, and A.A. Lacis, 1989: Global, seasonal cloud variations from satellite radiance measurements. Part I: Sensitivity of analysis. *J. Climate*, 2, 419-458.
- Rottman, G.J., 1988: Observations of solar UV and EUV variability. *Adv. Space Res.*, 7, 53-66.
- Sagan, C., O.B. Toon, and J.B. Pollack, 1979: Anthropogenic albedo changes and the earth's climate. *Science*, 206, 1363-1368.
- Salby, M.L., 1982: Sampling theory for asynoptic satellite observations. Part I: Space-time spectra, resolution, and aliasing. *J. Atmos. Sci.*, 39, 2577-2600.
- Salby, M.L., 1988a: Asynoptic sampling considerations for wide-field-of-view measurements of outgoing radiation. Part I: Spatial and temporal resolution. *J. Atmos. Sci.*, 45, 1176-1183.
- Salby, M.L., 1988b: Asynoptic sampling considerations for wide-field-of-view measurements of outgoing radiation. Part II: Diurnal and random space-time variability. *J. Atmos. Sci.*, 45, 1184-1204.
- Salby, M.L., 1989: Climate monitoring from space: Asynoptic sampling considerations. *J. Climate*, 2, 1091-1105.
- Sassen, K., 1992: Evidence for liquid-phase cirrus cloud formation from volcanic aerosols: Climatic implications. *Science*, 257, 516-519.
- Schlesinger, M.E., and J.F.B. Mitchell, 1987: Climate model simulations of the equilibrium climatic response to increased carbon dioxide. *Rev. Geophys.*, 25, 760-798.
- Self, S., and M.R. Rampino, 1988: The relationship between volcanic eruptions and climate change: Still a conundrum? *Eos*, 69, 74-75, 85-86.
- Sèze, G., and W.B. Rossow, 1991a: Time-cumulated visible and infrared radiance histograms used as descriptors of surface and cloud variations. *Int. J. Remote Sensing*, 12, 877-920.
- Sèze, G., and W.B. Rossow, 1991b: Effects of satellite data resolution on measuring the space-time variations of surfaces and clouds. *Int. J. Remote Sensing*, 12, 921-952.

- Shin, K.-S., and G.R. North, 1988: Sampling error study for rainfall estimate by satellite using stochastic model. *J. Appl. Meteor.*, **27**, 1218-1231.
- Shin, K.-S., G.R. North, and P.A. Arkin, 1990: Time scales and variability of area-averaged tropical oceanic rainfall. *Mon. Wea. Rev.*, **118**, 1507-1516.
- Simpson, J., R.F. Adler, and G.R. North, 1988: A proposed tropical rainfall measuring mission (TRMM) satellite. *Bull. Amer. Meteor. Soc.*, **69**, 278-295.
- Smith, W.L., 1970: Iterative solution of the radiative transfer equation for the temperature and absorbing gas profile of an atmosphere. *App. Opt.*, **9**, 1993-1999.
- Smith, W.L., and R. Frey, 1990: On cloud altitude determinations from high resolution interferometer sounder (HIS) observations. *J. Appl. Meteorol.*, **29**, 658-662.
- Smith, P.H., and M.G. Tomasko, 1984: Photometry and polarimetry of Jupiter at large phase angles II. Polarimetry of the South Tropical Zone, South Equatorial Belt, and the polar regions from Pioneer 10 and 11 missions. *Icarus*, **58**, 35-73.
- Somerville, R.C.J., and L.A. Remer, 1984: Cloud optical thickness feedbacks in the CO<sub>2</sub> climate problem. *J. Geophys. Res.*, **89**, 9668-9672.
- Stolarski, R.S., P. Bloomfield, R.D. McPeters, and J.R. Herman, 1991: Total ozone trends deduced from Nimbus 7 TOMS data. *Geophys. Res. Lett.*, **18**, 1015-1018.
- Takano, Y., and K.N. Liou, 1992: The effects of small ice crystals on cirrus infrared radiative properties. *J. Atmos. Sci.*, **49**, 1487-1493.
- Tanre, D., C. Devaux, M. Herman, and R. Santer, 1988: Radiative properties of desert aerosols by optical ground-based measurements at solar wavelengths. *J. Geophys. Res.*, **93**, 14,223-14,231.
- Tanre, D., J.F. Geleyn, and J. Slingo, 1984: First results of the introduction of an advanced aerosol-radiation interaction in the ECMWF low resolution global model. In, *Aerosols and their Climatic Effects*. Eds. H. E. Gerber and A. Deepak, Deepak Publ., Hampton, Va., pp. 133-177.
- Tiao, G.C., G.C. Reinsel, J.H. Pedrick, G.M. Allenby, C.L. Mateer, A.J. Miller, and J.J. DeLuisi, 1986: A statistical trend analysis of ozonesonde data. *J. Geophys. Res.*, **91**, 13,121-13,136.
- Tomasko, M.G., and L.R. Doose, 1984: Photometry and polarimetry of Saturn from Pioneer 11: Observations and constraints on the distribution and properties of cloud and aerosol particles. *Icarus*, **58**, 1-34.
- Tomasko, M.G., and P.H. Smith, 1982: Photometry and polarimetry of Titan: Pioneer 11 observations and their implications for aerosol properties. *Icarus*, **51**, 65-95.
- Toon, O.B., and J.B. Pollack, 1980: Atmospheric aerosols and climate. *American Scientist*, **68**, 268-278.
- Trenberth, K.E., 1990: Recent observed interdecadal climate changes in the northern hemisphere. *Bull. Amer. Meteor. Soc.*, **71**, 988-993.
- Tselioudis, G., W.B. Rossow, and D. Rind, 1992: Global patterns of cloud optical thickness variation with temperature. *J. Climate*, **5**, 1484-1495.

- Twomey, S.A., M. Piepgrass, and T.L. Wolfe, 1984: An assessment of the impact of pollution on global cloud albedo. *Tellus*, **36B**, 356-366.
- USGCRP, 1993: *Our Changing Planet: The FY 1993 U.S. Global Change Research Program*. Committee on Earth and Environmental Sciences, National Science Foundation, Washington, D.C., 79 pp.
- Vanderbilt, V.C., L. Grant, L.L. Biehl, and B.F. Robinson, 1985: Specular, diffuse, and polarized light scattered by two wheat canopies. *Applied Optics*, **24**, 2408-2418.
- Velasco, I., and J.M. Fritsch, 1987: Mesoscale convective complexes in the Americas. *J. Geophys. Res.*, **92**, 9591-9613.
- Wang, W.C., Y.L. Yung, A.A. Lacis, T. Mo, and J.E. Hansen, 1976: Greenhouse effects due to man-made perturbations of trace gases. *Science*, **194**, 685-690.
- Warren, S.G., C.J. Hahn, J. London, R.M. Chervin, and R.L. Jenne, 1986: Global distribution of total cloud and cloud type amounts over land. 29 pp. + 200 maps, (NTIS number DE87-00-6903).
- Warren, S.G., C.J. Hahn, J. London, R.M. Chervin, and R.L. Jenne, 1988: Global distribution of total cloud and cloud type amounts over the ocean. 42 pp. + 170 maps, (NTIS number DE90-00-3187).
- Watson, R.T., and Ozone Trends Panel, M.J. Prather and Ad Hoc Theory Panel, and M.J. Kurylo and NASA Panel for Data Evaluation, 1988: Present state of knowledge of the upper atmosphere, 1988: An assessment report.
- WCP-55, 1983: World Climate Research Program Report of the Experts Meeting on Aerosols and Their Climatic Effects, WMO, Williamsburg, 28-30 March 1983.
- WCRP, 1986: Scientific Plan for the World Ocean Circulation Experiment, WCRP Series No. 6. WMO/TD no. 122.
- Wielicki, B.A., and L. Parker, 1992: On the determination of cloud cover from satellite sensors: The effect of sensor spatial resolution. *J. Geophys. Res.*, **97**, 12,799-12,823.
- Wigley, T.M.L., 1988: The climate of the past 10,000 years and the role of the sun. In, *Secular Solar and Geomagnetic Variations in the Last 10,000 Years*. Eds. F. R. Stephenson and A. W. Wolfendale, Kluwer Publ., pp. 209-224.
- Wigley, T.M.L., and P.M. Kelly, 1990: Holocene climatic change,  $^{14}\text{C}$  wiggles and variations in the solar irradiance. *Phil. Trans. R. Soc. Lond. A*, **330**, 547-560.
- Willson, R.C., 1984: Measurements of solar total irradiance and its variability. *Space Sci. Rev.*, **38**, 203-242.
- Willson, R.C., and H.S. Hudson, 1988: Solar luminosity variations in solar cycle 21. *Nature*, **332**, 810-812.
- Willson, R.C., and H.S. Hudson, 1991: The sun's luminosity over a complete solar cycle. *Nature*, **351**, 42-44.
- WMO, 1990: *Scientific Assessment of Stratospheric Ozone: 1989*. World Meteorological Organization Global Ozone Research and Monitoring Project - Report, No. 20, WMO, Geneva.



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13. ABSTRACT (Maximum 200 words)  A workshop on Long-Term Monitoring of Global Climate Forcings and Feedbacks was held February 3-4, 1992, at NASA's Goddard Institute for Space Studies to discuss the measurements required to interpret long-term global temperature changes, to critique the proposed contributions of a series of small satellites (Climsat), and to identify needed complementary monitoring. The workshop concluded that long-term (several decades) of continuous monitoring of the major climate forcings and feedbacks is essential for understanding long-term climate change. The existing meteorological and planned ocean observing systems must be maintained, but they will not provide measurements of all the major climate forcings and feedbacks with the required accuracy over the appropriate time scales. Climsat would be able to monitor most of the climate forcings and feedbacks not monitored by current and planned observation systems, but would need to be supplemented by solar monitoring from space, tropospheric aerosol and ozone profile monitoring from selected surface stations, and improved calibration of radiosonde measurements of tropospheric water vapor profiles. The workshop emphasized that Climsat is complementary to the planned global change research program, including the EOS mission, and that strong support of researchers should be an integral part of the implementation of Climsat.				
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