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Atmospheres Panel Report to the Payload Panel

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Preface

This report is the outgrowth of the Atmospheres Panel meeting held in September 1991. The Panel was asked to either endorse or reject the CEES and IPCC research priorities for global change and to indicate which EOS candidate instruments, in the Panel's opinion, made the most significant contributions to answering the scientific questions associated with the CEES and IPCC priorities.

After some discussion, the Panel endorsed the CEES and IPPC priorities as presented by Dr. Watson at the Seattle IWG. However, the Panel remained very concerned about significant weakness in the proposed stratospheric instrument package associated with hydroxyl and halogen measurements. This concern is expressed in our recommendation list below.

This report is divided into five sections. The first section is a summary of recommendations of the Panel. The summary contains the list of primary instruments needed to answer the major science questions which the Panel has identified. The four sections following detail our recommendations. They are: (1) Clouds, Radiation and Precipitation, (2) Tropospheric Chemistry, (3) Stratospheric Chemistry and Dynamics and (4) Data Assimilation. While the separation of these issues may seem artificial, these four categories represent the cores of merging disciplines within the atmospheric sciences. In order to expose the reasoning behind instrument prioritization, the Panel reiterated the key science questions and then discussed the approach used to answer those questions. From the approach, measurement needs and instrument priorities follow logically. Additional subsections briefly discuss constraints on the remote measurements (if any) and other relevant measurement programs (if any); major recommendations follow.

EOS instruments matching the data requirements for a given science objective are divided into three categories: Primary, Ancillary and Contributing. The order of listing within the category does not indicate prioritization; it is random. A Primary Instrument is one directly relevant to the core science questions. A Contributing Instrument is one whose measurement would add to the overall pool of information in a positive way, but loss of data from that instrument would not cripple the science objectives as would loss of data from a Primary Instrument. Ancillary Instruments occupy the gray area in between. The Panel recognizes the measurements made by Ancillary Instruments as contributing significantly to some science objectives, but not all Panel members felt that an ancillary instrument was core to a given science objective.

I. Summary recommendations

The summary instrument priorities and recommendations below are reproduced from subsequent sections. Only the major recommendations are given.

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A. Instrument priorities

= means instrument on left preferred. * or + means group of instruments, or several instruments. 4D Assim = 4D Data Assimilation needed to answer science question. ( ) means see note in relevant section

Science Question Core Instruments	Ancillary	Contributing
Clouds and Radiation		
1. *Clouds and Radiation*		
CERES*, MODIS-N, MIMR, SAGE III, AIRS + , MISR, HIRDLS	LAWS = GLRS	HIRIS = ASTER
2. *Cloud Formation*		
MODIS-N, MIMR, AIRS + , 4-D Assim	LAWS, SAGE III LAWS = GLRS	
3. *Precipitation*		
MIMR, Rain Radar, AIRS + , 4-D Assim	LAWS, MODIS-N	LIS
4. *Aerosols and Radiation*		
MISR/EOSP, SAGE III*, CERES	GLRS, MODIS-N	HIRDLS
Tropospheric Chemistry		
1. *Changes in greenhouse gases*		
TES, MOPITT		
2. *Tropospheric Ozone and precursors*		
TES, MOPITT	SAGE III, HIRDLS	
3. *Oxidizing Capacity*		
TES, AIRS + , MOPITT SOLSTICE	HIRDLS, SAGE III	
4. *Sources of reactive gases*		
TES, MODIS-like imager 4-D ASSIM	AIRS + , MIMR (rain) MISR/EOSP, Scatterometer	
Stratospheric Chemistry and Dynamics		
1. *Long Term O_3 Trend*		
SAGE III (1)	HIRDLS, MILS, SAFIRE	
2. *Global Mapping O_3*		
HIRDLS = MLS, SAFIRE (2) 4-D Assim	TES(7)	AIRS/AMSU
3. *Global Mapping H_2O*		
HIRDLS-MLS, SAFIRE (2) 4-D Assim		
4. *Global Mapping T*		
HIRDLS-MLS SAFIRE (2) AIRS + , 4D Assim		GGI, SAGE III
5. *Radicals*		
OH		
SAFFIRE, (MLS) (3)		

ClO, (BrO)	OClO
MLS	SAGE III (4)
NO_2	NO_3
HIRDLS, SAFIRE, MLS	SAGE III (4)
6. *Reservoirs*	
HCl	$ClONO_2$ (5)
MLS, SAFIRE	HIRDLS
HF	HNO_3 (5)
SAFIRE, (MLS) (3)	HIRDLS, SAFIRE
7. *Source Gases*	
N_2O	CFC's (6)
HIRDLS, SWIRLS	HIRDLS
CH_4	
HIRDLS, SAFIRE	
8. *Other physical processes*	
Aerosols/PSC's	
SAGE III (6)	HIRDLS
Winds	
SWIRLS, 4D Assim	
UV Flux	
Solstice II	

Data Assimilation

1. *Atmospheric*		
temperature, winds, etc.		
AIRS + , LAWS, HIRDLS	Scatterometer	MODIS-N, MISR/EOSP
SWIRLS	CERES, SAGE III	
2. *Hydrologic cycle*		
AIRS + , LAWS,	MIMR, TRMM	MODIS-N, CERES
Scatterometer		MISR/EOSP
Rain Radar		
3. *Atmospheric Chemistry*		
SAGE III, HIRDLS, TES	SWIRLS, LAWS	
MLS, SAFIRE, MOPITT	AIRS +	
4. *Oceans*		
and Surface Fluxes		
Scatterometer, LAWS	AIRS + , MODIS-N	CERES

B. Major recommendations

Clouds and radiation

1. High priority should be given to Earth Radiation/Cloud instrument package which includes CERES, AIRS + , MIMR, MISR/EOSP, and MODIS-N. In addition, an inclined orbiting SAGE III (and/or polar orbiting HIRDLS) is needed for cloud aerosol and upper tropospheric water vapor and ozone studies.

2. MODIS-N cannot be replaced by AVHRR as the cloud imager on the afternoon orbit satellite. AVHRR is critically deficient for calibration, cloud particle size, cirrus cloud altitude, multi-level cloud systems, and boundary layer clouds. The critical synergism is CERES/MODIS-N/MIMR/AIRS + and must be provided on at least one of the three spacecraft providing diurnal sampling.

3. Accuracy of monthly averaged radiation budget quantities will be significantly improved if CERES is on the NASA am orbiting satellite with MODIS-N as opposed to the ESA platform with AVHRR + HIRS. For the second series of satellites, CERES + MODIS-N + MIMR is desired for all three spacecraft.

4. An early flight of MIMR would allow an overlap of at least 1 year with the TRMM radar for calibration of rainfall measurements.

5. Either GLRS or LAWS are highly desirable for measurements of polar cloud amount/height, planetary boundary layer height, three-dimensional cloud structure, and aerosol profiles. They will probably provide the only accurate cloud height information for polar region process studies.

6. MODIS-T cannot provide sufficient samples of cloud anisotropy in place of MISR.

Tropospheric chemistry

1. Fly MOPITT and TES as soon as possible along with instruments which measure surface processes and ocean color (e.g. MODIS-N).

2. MOPITT should be flown with AIRS + for cloud location and temperature profiles.

Stratospheric chemistry

1. Two SAGE III instruments be flown. One for long term ozone monitoring in a high inclination orbit, and a second for polar PSC and ozone measurements in polar orbit.

2. HIRDLS be flown as soon as possible.

-To provide continued global monitoring of the major trace gases in the stratosphere: O_3, H_2O, CH_4, N_2O, NO_2, $ClONO_2$, HNO_3, CFC's

—To provide high vertical and horizontal resolution temperature measurements throughout the stratosphere. No temperature measurements will be available for the upper stratosphere after UARS and the last SSU.

—NOAA has expressed an interest in flying subsequent copies of HIRDLS as the GOMR instrument.

3. No decisions be made concerning the EOS-B stratospheric instruments (MLS, SAFIRE, SWIRLS) until 1 year after UARS has flown. This would allow instrument investigators for SAFIRE, MLS and SWIRLS to refocus their instruments on key problems identified by UARS measurements and key molecules identified by the Panel for monitoring. The Panel notes that while the combination of SAGE III and HIRDLS provides a significant amount of stratospheric information, information on the chlorine radicals and reservoirs and on the hydroxyl radical is lacking. The Panel views these measurements as ESSENTIAL to the success of any strategy focussing on global change. Furthermore, this data void will not be filled by foreign instruments.

Data Assimilation

1. AIRS + should fly on the first platform since it provides the most direct path to addressing the validation issues for GCM parameterizations which led to the highest priority IPCC and CEES questions.

2. Accurate assimilated winds greatly enhance our ability to understand the hydrologic cycle. Thus the Panel sees LAWS as a critical component of EOS. Without atmospheric moisture transport and convergence estimates which "explain" observed regional precipitation patterns in the current climate we will be unable to estimate the accuracy of GCM simulated changes in the hydrologic cycle.

3. Scatterometer data from ERS-1 should undergo detailed evaluation in terms of data assimilation derived surface stresses before any nonreversible decisions are made regarding STIKSCATT.

4. For chemical assimilation the stratospheric/tropospheric package is required.

II. Clouds, radiation and precipitation

Science questions

1. Can we accurately observe and predict the effect of cloud physical properties on the radiative energy fluxes at the surface of the earth, within the atmosphere, and at the top of the atmosphere?

2. Can we accurately observe and predict cloud formation and dissipation given atmospheric state variables including: temperature, water vapor, winds (especially vertical velocity and shear), and aerosol amount?

3. Can we accurately observe and predict the amount of precipitation given atmospheric state variables and aerosol amount? Can we use precipitation as a tracer of latent heat release in the atmosphere?

4. Can we accurately observe and predict the effect of natural and anthropogenic aerosols on the radiative energy fluxes, both directly and through their effect on cloud microphysics?

Method / approach

Climate monitoring is achieved through the use of global satellite and regional surface observations of key cloud/climate parameters. Desired time and space scales for EOS global satellite monitoring observations are monthly averaged values within approximately 100 km square regions. These data are used to monitor climate and to test the accuracy of global climate models. Climate models are tested against the present climate for spatial variations (regional climate) as well as temporal variations (diurnal, seasonal, and multiyear signals such as ENSO (El-Nino Southern Oscillation). Primary variables to be measured for studies of clouds, radiation, and precipitation are:

(a) radiative fluxes at the surface, within the atmosphere, and at the top of the atmosphere for both shortwave and longwave radiation. (b) cloud properties, including cloud amount, height, thickness, optical depth, particle size, liquid and ice water path, aspect ratio, and by combination with the radiative flux data, cloud albedo and cloud emitted longwave flux, (c) precipitation, (d) atmospheric state variables including profiles of temperature, water vapor and winds, (e) aerosol optical depth, particle size, single scatter albedo for tropospheric and stratospheric aerosols, (f) greenhouse gases, including H_2O, CO_2, O_3, CH_4, CFC's.

Atmospheric state variables critical to studies of clouds and radiation include measurements of profiles of temperature, water vapor, and winds. Four-dimensional assimilation of this data in a dynamical forecast model will be used to estimate vertical wind component, and to improve water vapor estimates. A more complete discussion can be found in the section on 4-D assimilation.

Cloud process studies are performed in two primary modes: cloud scale and regional scale studies. Figure 1 demonstrates the relationship between EOS satellite observations and their use in both cloud monitoring and cloud process studies.

Cloud scale studies are performed primarily on field experiment data collected on the space and time scales of individual cloud elements. Cloud scale models have the most complete cloud physics and may resolve spatial scales as small as 100 meters. These models are typically validated against individual case study observations based on aircraft, surface and balloon. Because of the limited amount of data used to verify cloud process models, hypotheses developed from a few case studies require testing with longer time series data (satellite or ARM) and over a larger portion of the earth (satellite). Regional scale cloud studies are often conducted in conjunction with field experiment data but require coverage of larger spatial scales of about 50–1000 km. Regional scale models (often termed "mesoscale" models) are more sophisticated versions of global weather prediction models, and can be run in forecast mode using instantaneous atmospheric state data. They typically incorporate more complete physics at higher spatial and temporal resolutions (10–50 km) and represent an intermediate step between global and cloud scale modeling efforts. Regional scale studies require satellite cloud observations to supplement the limited spatial coverage of surface and aircraft observations.

Satellite measurements required to support process studies are almost the same as given above for the monitoring studies. The major exception is that the time-averaged monitoring data (critical to monitor energy and water budgets) require sampling from three satellite orbits in order to accurately account for the large diurnal cycle of clouds, radiation, and precipitation. Process studies require observations of high spatial and temporal resolution. EOS-A will provide the highest spatial resolution observations, while Geostationary satellites will be relied on for the high temporal resolution. Unfortunately, the factor of 50 difference in orbit altitude limits the accuracy and spatial resolution which can be obtained by the Geostationary satellites, thereby requiring the more accurate EOS-A data for many cloud process studies. In general, both satellite systems are required.

The atmospheric state variables implied in Fig. 1 include temperature, water vapor, winds, aerosols, and greenhouse gases. Climate feedbacks involving greenhouse gases represent a link in the climate system between the cloud processes discussed above, biogeochemical cycles (especially CO_2), atmospheric chemistry (O_3), and land processes (H_2O). These last three processes are discussed in other reports.

What will be known prior to EOS?

ISCCP, ERBE, and SSM/I will provide the major pre-EOS data sets for cloud, radiation, and precipitation. AVHRR and CZCS provide the major sources of lower tropospheric aerosol (poorly known), while SAM II, SAGE I and SAGE II provide upper tropospheric and stratospheric aerosol (accurately known). At present, the ISCCP and ERBE data provide cloud and radiation data which is more accurate than current global climate model simulations. Regional and zonal cloud cover can be in error as much as 50%. Regional and zonal cloud radiative forcing can be in error by as much as 50 Wm^{-2}. Pre-EOS field experiments (FIRE, ARM, GEWEX, TOGA), along with this satellite data will provide significant advances in our understanding of three types of cloud fields; midlatitude cirrus over land, stratocumulus over ocean, and tropical convective cloudiness over ocean. Efforts are underway to estimate cloud particle size for stratocumulus clouds using AVHRR data in order to quantify the possible effect of anthropogenic aerosols on cloud albedo. Key problem areas which are likely to require EOS data for accurate measurements include:
global precipitation, surface radiative fluxes (up, down, net), within-atmosphere radiative fluxes, accurate polar cloudiness and radiation budget, resolution of multilevel cloud situations (approximately half of all cloud observations) including cloud overlap, cloud particle size measurements (water and ice cloud), three-dimensional (non-plane-parallel) cloud structure effect on radiation, cirrus cloud altitude, extent, and optical thickness, cloud thickness (all types), cloud liquid and

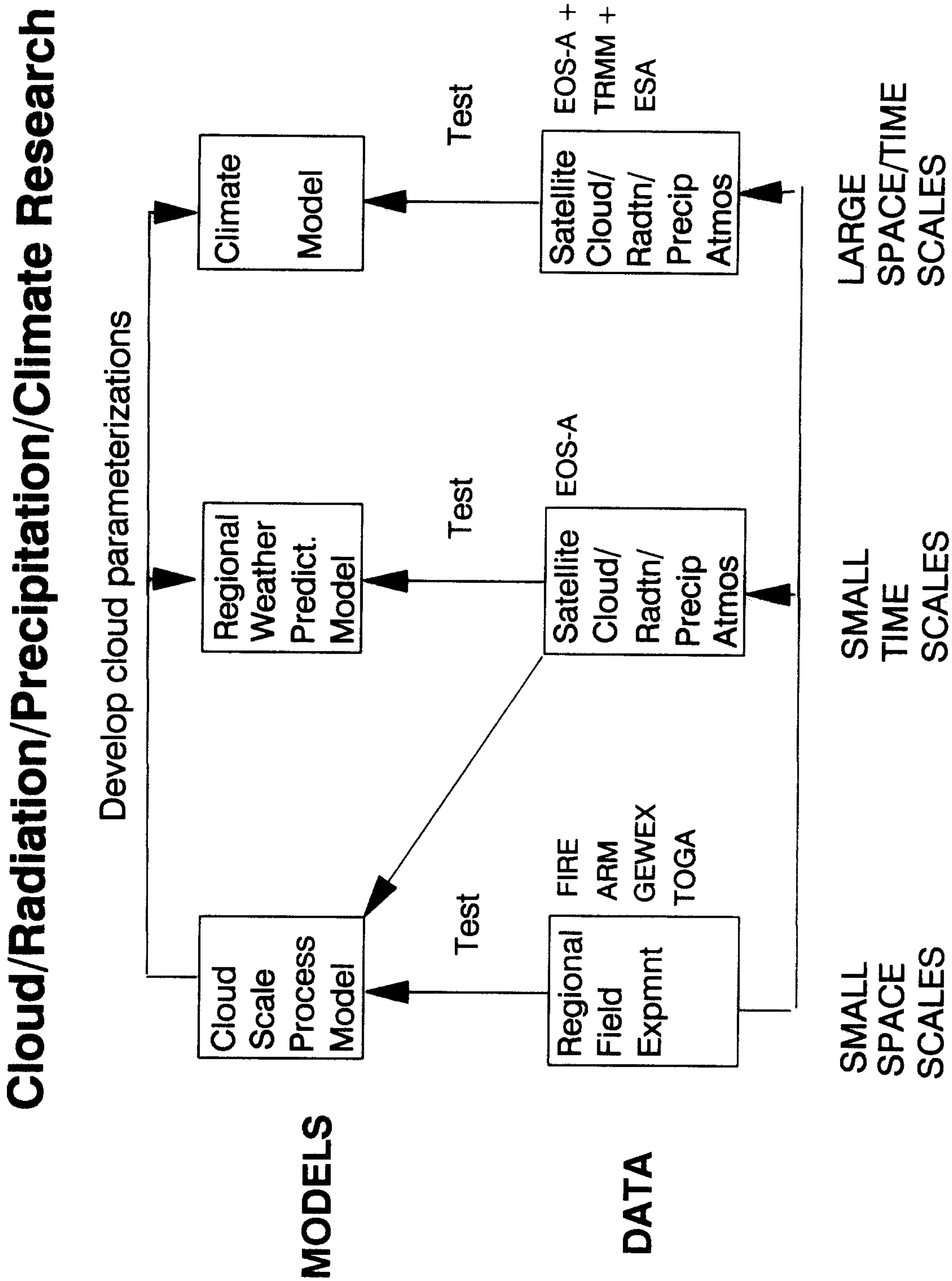

Fig. 1. Cloud/radiation/precipitation/climate research.

ice water contents, aerosol properties (optical depth, single scatter albedo), vertical distribution of atmospheric water vapor, vertical wind profiles, O_3 in the upper troposphere and lower stratosphere.

These are the key areas which must be addressed by EOS and give rise to the instrument requirements given in the next section.

Instrument needs

In order to answer the science questions, the following instruments are required.

Science Question Core Instruments	Ancillary	Contributing
1. *Clouds and Radiation*		
CERES*, MODIS-N, MIMR, SAGE III, AIRS + , MISR, HIRDLS	LAWS = GLRS	HIRIS = ASTER
2. *Cloud Formation*		
MODIS-N, MIMR, AIRS + , 4-D Assim	LAWS, SAGE III LAWS = GLRS	
3. *Precipitation*		
MIMR, Rain Radar, AIRS + , 4-D Assim	LAWS, MODIS-N	LIS
4. *Aerosols and Radiation*		
MISR, EOSP, SAGE III, CERES	GLRS, MODIS-N	

Notes: AIRS + is a set of sounding instruments including AIRS, AMSU, and MHS; CERES* is two scanning instruments on the same spacecraft, one sampling space, one sampling viewing angle, 4-D Assim is the use of a dynamical forecast model to improve the self consistency of atmospheric profiles of temperature and wind, as well as to interpolate in time between observations.

Capabilities of the instruments for each science question can be summarized as follows:

1. **Clouds and Radiation**

CERES*	Broadband radiation
MODIS-N	Cloud physical properties (amount, height, optical depth, particle size and phase)
MIMR	cloud liquid water path and cloud thickness (with MODIS-N)
AIRS +	Temperature and water vapor profiles, spectral surface and cloud emittance
MISR	3-D cloud structure and anisotropy, stereo cloud heights, impact on radiation budget
SAGE III	Upper troposphere/lower stratosphere water vapor and ozone profiles (greenhouse gases)
HIRDLS	Upper tropospheric/lower stratospheric ozone and water vapor (green house gases)
LAWS = GLRS	Improved cloud heights: polar and multi-level clouds
HIRIS = ASTER	Improved small scale cloud properties

2. **Cloud Formation**

MODIS-N	Cloud physical properties (as in (1) above).
MIMR	cloud liquid water path and cloud thickness (with MODIS-N)
AIRS +	Temperature and water vapor profiles, spectral surface and cloud emittance
4-D Assim	Improved water vapor and wind profiles (including vertical velocity)
LAWS	Improves the accuracy of all 4-D assimilation products over ocean and in the S. Hemisphere
SAGE III	Most accurate upper troposphere water vapor
LAWS = GLRS	Improved cloud heights: polar and multi-level clouds, planetary boundary layer heights

3. Precipitation

MIMR	Precipitation measurements over ocean, less accurate over land
Rain Radar	Calibration of MIMR, together with MIMR, provides precip over land and ocean
AIRS +	Temperature and water vapor profiles, spectral surface and cloud emittance
4-D Assim	Improved water vapor and wind profiles (including vertical velocity)
LAWS	Improves the accuracy of all 4-D assimilation products over ocean and in the S. Hemisphere
MODIS-N	Precipitation estimates using thermal thresholds which may improve accuracy for convection over land
LIS	Lightning measurement to potentially improve precipitation measurements over land

4. **Aerosols and Radiation**

MISR	Estimates of topospheric aerosol properties using multi-wavelength multi-angle views.
EOSP	Estimates of tropospheric aerosol properties using multi-wavelength polarization
SAGE III	Stratospheric and upper tropospheric aerosol profiles
CERES	Broadband radiative effects of aerosols
MODIS-N	Estimates of tropospheric aerosol properties using multi-wavelength, multiple time views
GLRS	Improved vertical structure of tropospheric aerosols but uncertain properties (size, single scatter albedo)

Orbit constraints

Orbit constraints identify the time sampling requirements of the instruments, as well as synergisms between multiple instruments used to address a single science question. The science question number is given for each requirement.

(a) Space and time variations in cloud optical depth require cloud process studies to obtain data simultaneously within about 2 minutes. Key synergisms are: MODIS-N, CERES, and MIMR for cloud/radiation (1) MISR, MODIS-N for cloud anisotropy and aerosols (1), (4).

(b) AIRS/AMSU/MHS atmospheric profile data is required within 5–10 minutes of cloud and radiation information (CERES/MODIS-N/MIMR) (2).

(c) GLRS or LAWS should observe a cloud target within 5–10 minutes of MODIS-N and CERES for studies of cloud radiative properties and validation of MODIS-N cloud heights (1).

(d) CERES + and a cloud imager/sounder are required on three spacecraft; a.m. and p.m. sunsynchronous orbits plus one inclined orbit. (1)

(e) Passive microwave is required on three spacecraft; a.m. and p.m. sunsynchronous orbits plus one inclined orbit. (3)

(f) A rain radar (either on TRMM or a later Japanese inclined orbiting platform) must overlap for at least one year with the MIMR passive microwave in order to calibrate precipitation measurements. (3)

(g) SAGE III should fly on at least two spacecraft, one in sunsynchronous orbit for polar sampling, and one in an inclined orbit for sampling in the tropics and midlatitude (1, 3, 4).

Other instruments / programs

SCARAB: French/Soviet experiment to provide ERBE-type measurements of broadband radiation in 1994-1995. Calibration problems have delayed this experiment. If successful will cover some of the data gap between ERBE and EOS CERES. No cloud imager with instrument for cloud - radiation type measurements.

POLDER: multi-angle polarimeter for ADEOS in 1995. POLDER lacks spectral coverage of EOSP for aerosols over land and self calibration for long term monitoring.

Recommendations

1. LIS may provide information essential to accurate precipitation measurement over land, and should be flown on TRMM to test this concept.

2. MISR, EOSP, MODIS-N, and GLRS provide complementary measurements of aerosols. Even though anthropogenic aerosols might currently cause a global radiative impact as large as CO_2 increases, there is no accepted method to remotely sense lower tropospheric aerosol properties (SAGE III can accurately profile stratospheric aerosols). Any of the four instruments would provide a significant advance over current data, but aerosol measurements are too poorly understood to assure success with any single instrument. GLRS is the only instrument which could observe aerosols at night.

3. Observing system assimilation experiments (OSSE's) show that the tropical oceans and the entire

southern hemisphere have errors for winds which are a factor of 3 larger than obtained over the northern hemisphere continents because of the scarcity of rawinsonde data in these regions. OSSE's indicate that AIRS + would reduce the error by roughly one third below that obtained with current data. LAWS winds would provide an additional reduction of one third thereby achieving accuracies equivalent to a global rawinsonde network. Even larger improvements from LAWS in such important quantites such as moisture transport can be expected. LAWS is therefore essential to global studies of cloud formation and precipitation.

II. Tropospheric chemistry

Science questions

Four scientific issues form the focus for EOS investigations of tropospheric chemistry. Besides trace gases in the atmosphere and their role in chemical and radiative processes, tropospheric chemistry questions are closely connected to some issues identified by the Biogeochemistry, Oceans and Hydrology Panels. This is because synoptic scale transport, clouds and surface exchange processes play major roles in the fluxes and transformations in the lower atmosphere.

1. Trace gases and climate—global warming
What is the source distribution of radiatively active gases with natural and anthropogenic origins: CH_4, N_2O, CO_2? What is natural and anthropogenically-induced variability in ecosystems due to potential changes in temperature, acid deposition, rainfall, uv radiation?

2. Tropospheric ozone and global pollution
What is natural variability in tropospheric ozone? —What are magnitudes of ozone production from industrial activity and biomass burning?—What are roles of convection, stratosphere-troposphere exchange and long-range transport in O_3 formation?—Is tropospheric O_3 increasing? Are its precursors, CO, NO_x, and hydrocarbons increasing—What is effect of O_3 change on forests, agriculture, ecosystems?

The single most important global change question in the troposphere is "is tropospheric O_3 increasing?" Evidence from surface observations suggest that in parts of the Northern Hemisphere O_3 in the lower troposphere is on the rise. Examination of the ozonesonde record for several sites where there are long-term records is less conclusive. In the Southern Hemisphere, there may be temporal decreases in surface O_3 in recent years associated with South Polar stratospheric O_3 depletion. The satellite observations to date—the so-called "tropospheric residual" record obtained from differencing SAGE and TOMS data - strongly suggests temporal increases in tropospheric O_3 in the tropics over the past decade. EOS must determine whether or not tropospheric O_3 is increasing.

3. Is the oxidizing capacity of the atmosphere changing?
What are spatial distributions of OH and H_2O_2 in the troposphere? What is total OH abundance? Does it change over the EOS observing period?

OH oxidizes virtually everything with an extractable H atom. It controls the lifetime of the hydrogenated CFC substitutes. Thus, if OH increases, fewer HCFCs will penetrate to the stratosphere; conversely, if global OH decreases, more HCFCs will make it to the stratosphere. The OH radical also leads to the formation of organic, sulfuric and nitric acids in the atmosphere. Tropospheric distributions of OH cannot be measured directly but must be inferred from O_3, UV, H_2O, CH_4, CO and temperature.

4. What are the budgets and sources of C-, S-, and N-containing trace gases?
—What are terrestrial and oceanic contributions to global carbon cycle? What are inputs of atmospheric C, N and S from soils, vegetation, wetlands, lightning? —What is the anthropogenic contribution to these trace gases and how is it distributed?—Are there trends in emissions of radiatively and photo-reactive gases, both natural and anthropogenic?—Is there large-scale interaction of clouds and precipitation with trace gases?—What is the effect of volcanoes in supplying trace gases and in influencing radiation?—What is role of the oceans in atmospheric sulfur (&sulfate aerosols) and what are climatic feedbacks to marine phytoplankton?

All of these "tropospheric chemistry" questions are clearly central to the highest priority of IPCC and CEES.

Method / approach

The minimum set of measurements required to answer each of the four "tropospheric questions" boil down to measurement of tropospheric trace gases which have an intermediate lifetime (days to months) from space. The concentration of shortlived trace gases, usually radicals, is inferred from UV flux and measurement of the intermediate lifetime gases along with an appropriate model and data assimilation. This method is validated by field campaigns where insitu measurements are made. Thus, in addition to the trace gases other sources of information are required such as ocean color, biomass burning, land vegetation etc.

What will be known prior to EOS?

Prior to the launch of EOS, field campaigns and existing satellite information should yield much more information on the relationship between various tropospheric gases, source gases, and the transformation process including the role of clouds, precipitation and aerosols.

(1) With stratospheric satellites (TOMS, UARS, etc.) and data assimilation we will learn more about stratosphere/troposphere trop exchange of trace gases.

(2) Tropospheric residual ozone can be approximated by SAGE/TOMS O_3 differential, giving information on regional and seasonal mid-troposphere ozone behavior.

(3) Surface fluxes of some land and ocean derived trace gases can be estimated using AVHRR, SeaWIFS and 4-D Assimilation.

Instrument needs

Science Question Core Instruments	Ancillary	Contributing
Changes in greenhouse gases		
TES, MOPITT		
Tropospheric Ozone and precursors		
TES, MOPITT	SAGE III, HIRDLS	LIS
Oxidizing Capacity		
TES, AIRS +, MOPITT	HIRDLS, SAGE III SOLSTICE	
Sources of reactive gases		
TES, MODIS-like imager 4-D ASSIM	AIRS +, MIMR (rain) MISR, EOSP, Scatterometer	

Other instruments/programs

Long lived tropospheric trace gases are best measured by the ALE/GAGE and NOAA/CMDL networks. The Japanese IMG instrument will supply global measurements of long lived trace gases for one year in the pre-EOS period.

Recommendations

See Section IB

III. Stratospheric chemistry and dynamics

Science questions

The primary science question associated with stratospheric chemistry is: Do we understand the evolution of stratospheric trace gas composition during a period of large anthropogenically forced changes in the stratosphere?

Subsidiary questions include:
—Can we understand/predict global ozone changes and the subsequent changes in UV flux?
—What is the role of polar ozone depletions in the overall ozone budget of the stratosphere?
—What is the impact of chlorine in the upper stratosphere during the EOS period when chlorine reaches unprecedented levels?
—What is the impact of aircraft exhaust (aerosols and NO_x) on the chemistry of the lower stratosphere?
—What impact will increasing greenhouse gases (mainly CO_2) and water source gases (CH_4) have on the chemistry and dynamics of the stratosphere?

Method/approach

The basic method of stratospheric research is the validation of current models and hypothesis through long term global monitoring of key stratospheric species and physical processes. Model validation occurs through the complementary activities of global satellite observations, aircraft and balloon insitu observations, and ground based methods. The Atmospheres Panel has identified the minimum measurement requirements for this monitoring. These requirements consist of a set of species which characterizes the main chemical cycles involving ozone, and measurements of the basic physical environment of the stratosphere (temperature, UV flux, winds etc.). The minimum chemical set is determined by a radical and a reservoir from each of the major chemical families (O_x, NO_x, ClO_x and HO_x), and the source gases for these families (e.g. N_2O for the NO_x family).

The physical environment measurement set includes:
Temperature, wind, UV flux and aerosol/cloud amounts.
The minimum set of chemical species are:
O_3, H_2O: Main players in atmospheric chemistry and radiation.
OH, NO_2, ClO: Major radicals from the HO_x, ClO_x and NO_x families.
HCl, HF: Halogen reservoirs.
N_2O, CH_4: Hydrogen and nitrogen source gases.
Other useful species include:
HNO_3: Additional significant nitrogen reservoir.
$ClONO_2$: Link between chlorine and nitrogen cycles.
BrO, OClO: Additional halogen radicals.

Measurement requirements differ for the different species and physical processes. Continuous global measurement of temperature, winds, aerosols/clouds, long lived trace gases, some radical and most reservoir species are needed since these quantities can vary spatially. Long term, high precision continuous monitoring of ozone, temperature and some reservoir gases is needed for global trends. High horizontal resolution measurements are not needed for long term trends, but near global coverage is required. Temperatures and long-lived trace gas measurements at high spatial resolution (about 2.5° long, 1° latitude, 3 km altitude) are needed to characterize the dynamics of the stratosphere through 4D data assimilation. In the tropics, direct wind measurements are needed.

What will be known prior to EOS?

The principal satellite program which will yield significant information on the state of the stratosphere prior to EOS is UARS (Upper Atmosphere Research Satellite). However, the operation period for UARS is planned for only three years although some measurements may continue beyond the three year lifetime. UARS will measure many of the important nitrogen and chlorine species in the middle and upper stratosphere. No measurements of the HO_x species will be made.

Additional long term monitoring of the stratosphere will continue through the NDSC (Network for Detection of Stratospheric Change). NDSC will use lidars and ground based instruments to compliment satellite measurements and provide information on global trends of some key radicals and reservoirs. Only five or so NDSC sites will be constructed so NDSC cannot produce global mapping.

Aircraft programs will provide significant information about the lower stratosphere. However, the aircraft campaigns are process oriented endeavors, making simultaneous insitu measurements of a large number of trace gases to validate chemical processes. They will provide complementary information to satellite observations.

ESA plans to launch several stratospheric instruments aboard the ATMOS Satellite and on EPOP. These programs are discussed further below, but the ESA proposed system will provide no new information over the EOS instrument complement, and the atmospheres Panel believes that these instruments are significantly riskier.

During the pre-EOS period the shuttle based ATLAS program will provide good "snapshots" of the stratosphere using a variety of instruments. ATLAS will provide basic information on a large number of molecules making up the entire chemical system and will help validate the chemical models. No ATLAS flights are planned during EOS.

Finally as part of the Earth Probes program and NOAA satellite series, SAGE II/III, TOMS and SBUV-2 provide ozone monitoring. TOVS (SSU, MSU and HIRS) and later the AMSU system will provide mid to lower stratospheric temperature data. The EOSDIS TOVS reprocessing activity will improve our characterization of the meteorological environment of the stratosphere.

Instrument needs

Science Question Core Instruments	Ancillary	Contributing
Long Term O_3 Trend		
SAGE III (1)	HIRDLS, MLS, SAFIRE	
Global Mapping O_3		
HIRDLS = MLS, SAFIRE (2)	TES (7)	AIRS/AMSU

Global Mapping H_2O		
HIRDLS = MLS, SAFIRE (2)		
Global Mapping T		
HIRDLS = MLS SAFIRE (2)		GGI, SAGE III
AIRS +		
Radicals		
OH		
SAFIRE, (MLS) (3)		
ClO, (BrO)	OClO	
MLS	SAGE III (4)	
NO_2	NO_3	
HIRDLS, SAFIRE, MLS	SAGE III (4)	
Reservoirs		
HCl	$ClONO_2$ (5)	
MLS, SAFIRE	HIRDLS	
HF	HNO_3 (5)	
SAFIRE, (MLS) (3)	HIRDLS, SAFIRE, MLS	
Source Gases		
N_2O	CFC's (6)	
HIRDLS, SWIRLS	HIRDLS	
CH_4		
HIRDLS, SAFIRE		
Winds		
SWIRLS		
UV Flux		
Solstice II		
Aerosols / PSC's		
SAGE III (6)	HIRDLS	

Notes: (1) Sage III in high inclination orbit similar to Sage II. (2) HIRDLS is an limb instrument like MLS and SAFIRE but scans horizontally thus making higher spatial resolution measurements than SAFIRE or MLS. As a result HIRDLS is preferred for these measurements. (3) MLS may have OH, HF measurement capability within the next few years. (4) Very useful radical. (5) Very useful reservoir species. (6) PSC measurements require SAGE III in polar orbit. (7) TES will provide important information of many stratospheric species but its coverage only includes the lower stratosphere. Thus in this regard it is categorized as ancillary.

Orbit Constraints

The stratospheric chemistry instruments, in general, have no orbital constraints except that they would prefer near noon crossing times. SAGE III is a solar occultation instrument. As a long term monitor of ozone, water vapor and aerosol trends, SAGE III is preferred in a high inclination orbit (55°). To monitor polar phenomena such as the ozone hole or PSC's, SAGE III in polar orbit is preferred.

Other instruments / programs

The Atmospheres Panel has examined the following foreign instruments proposed by ESA for EPOP and ATMOS. These instruments are discussed briefly below:

SCIAMACHY: UV limb, backscatter and nadir instrument. SCIAMACHY will make a number of measurements similar to SAGE and SBUV. The Panel felt that the instrument design showed significant risk.

MIPAS: An IR limb sounder using the FTIR approach. MIPAS will make measurements similar to HIRDLS but at lower spatial resolution.

GOMOS: Similar to SAGE III except uses stars. Panel members were concerned that the instrument's low signal to noise would restrict its contribution to ozone alone.

While the Panel was impressed with the technical competence of the ESA investigators and the ambitious efforts, the lack of space heritage on instrument design increases their risk. In addition, the combination of MIPAS, GOMOS, and SCIAMACHY yielded no new molecular information over the combination of HIRDLS and two SAGE III's. In addition, the spatial resolution of the measurements was lower (with the exception of SCIAMACHY in the nadir mode, in which case the information is similar to the NOAA SBUV-2).

Recommendations

See Section IB.

IV. Four-dimensional data assimilation

Science questions

Four-dimensional data assimilation is a fundamental method for the synthesis of diverse, temporally inconsistent, and spatially incomplete observations into a coherent representation of the evolving geophysical system. Data assimilation for the atmosphere is a proven strategy in an advanced state of development, and although in an early stage of development for the earth sciences as a whole, it is strategically situated to address the pressing national need to observe and understand global change as it occurs in the coming decades.

There are three major advantages of data assimilation.
(1) Through the use of models it is possible to produce a physically and chemically consistent data set. It is also possible to produce globally consistent fields of unobserved quantities (e.g. vertical velocity, chemical radicals).
(2) Because data assimilation is a dynamic process, it is possible to propagate information from data rich to data poor areas. Assuming that the forecast models are of sufficient quality, state representations in data poor regions are vastly improved. Furthermore, the impact of data poor regions on data rich regions is minimized.
(3) Through a combination of statistical methods and the forecast model, powerful techniques of quality control can be built.

Data assimilation suffers from both the imperfection of models and analysis techniques. These imperfections can, in fact, harm data sets if care is not taken. It has already been shown, however, that for many atmospheric process studies assimilation provides the most powerful approach.

Atmospheric data assimilation has been developed in the numerical weather prediction (NWP) community. Applications of the assimilated data sets to climate problems and atmospheric process studies are relatively new. A fundamental problem lies in the time scales involved. Assimilation techniques have been derived and optimized in a discipline where time scales of days are the highest priorities. EOS related problems require much longer time scales, from seasonal to decadal. How to apply assimilated data sets, and improvements in the assimilated data sets comprise an active research project in the prelaunch epoch. The extension of assimilation techniques to ocean, land surface, and chemical problems is another goal.

The combined use of assimilated data and interpretive models is an potent tool to address Earth Science problems. The data will constrain the models to form a credible representation of the system. Then the study of how the models and data diverge leads directly to the identification of the mechanisms that maintain the physical and chemical structure of the Earth System. This approach addresses both model problems and data problems.

Major Earth Science questions that will be addressed with assimilated data sets include:

1. How well do the assimilated data sets represents the global transport of heat, energy, and constituents? What are the important mechanisms of atmospheric transport? How can the transport characteristics be improved? Are the interactions between the tropics and middle latitudes properly represented?

2. What are the sources and mechanisms of interseasonal and interannual variability? Can these mechanisms be properly represented in assimilated data sets? How can climate models be improved to represent these mechanisms correctly?

It has already been shown that assimilated data products can have a profound impact on atmospheric transport and chemistry problems. Through these transport characteristics direct information on the general circulation, and the processes that maintain the general circulation, can be obtained.

Much more research must be done to assure that assimilation techniques can address a wide range of problems. The following problems can confidently be addressed with assimilation techniques:

1. Data constrained studies of cloud, precipitation, and radiative processes. These studies are directly related to the representation of diabatic forcing in the troposphere.

2. Improved representations of climate in poorly observed areas.

3. The generation of best estimates of unobserved quantities of geophysical interest.

4. Improvement of data retrieval algorithms by supplying accurate first guess fields.

5. Possible identification of sensitive parameters of climate change.

6. Quality control of data. Are our instantaneous observations, both insitu and space-based, consistent

and unbiased among themselves, and are observations derived from different or similar instruments on different satellites properly calibrated with each other?

Data assimilation becomes more important at the prospect that EOS data sets will not be as complete as originally proposed. Assimilation techniques have the capability of filling in holes in the data set. Of course they are limited by the imperfections of our physical and chemical understanding and the numerical representation of that understanding.

Method / approach

The approach to these problems will be multifaceted. A primary focus will be the production of data sets and their application to EOS related problems. Only through the application of data sets can their appropriate and inappropriate uses be determined. This will reveal the strengths and weaknesses of the assimilation approach.

Using the information obtained form these diagnostic applications (e.g. process studies), it will then be possible to explore assimilation parameter space. What are the impacts of:

(1) Analysis techniques,
(2) GCM numerics and physical parameterizations,
(3) Initialization techniques,
(4) Data preprocessing and error control?

There are a wide variety of choices to be made in all of the above algorithm components. Decisions will be made on algorithm choice and development based on improved capabilities to address EOS related problems. Success will be measured by producing analyses that are physically and chemically consistent, and in agreement with the fundamental mathematical basis of chemistry and physics.

Initial work will focus on atmospheric applications, and in particular on global transport characteristics and interseasonal and interannual variability. This builds out of the legacy of assimilation in atmospheric science. From this core future research will contain multiple foci on improved representation of hydrological processes, oceans, and surface processes.

An important component of the assimilation research will to be to produce data sets in a timely fashion so that they might be used in conjunction with the many surface based campaigns of the next 5–10 years. These campaigns provide high quality data sets, that are often more complete that satellite data. These data sets provide high quality verification data. They also more completely define the processes involved in the Earth system, and hence, they provide the data with which to assess and improve the physical and chemical mechanisms represented in the assimilated data sets.

What will be known prior to EOS?

The data prior to EOS provide the test bed in which to develop the assimilation system. Maximum use of the preEOS must be made to define what is needed in the assimilated data sets, and how well do the data sets address the important problems. It is possible that instead of one 'unified' data assimilation system, versatile smaller systems that adequately address particular processes will be developed.

Prior to the launch of EOS, baseline climate assimilation products for the years since 1979 will be created from the historical data base and their suitability for climate research thoroughly optimized. These prototype products and the assimilation techniques used in producing them will undergo periodic critical reviews by the climate diagnostic, assimilation, modeling, oceanographic, hydrologic and land surface communities.

Assimilation experiments will be undertaken to support dynamic modeling of stratospheric and tropospheric chemistry, to improve and validate tropical assimilation techniques using data from TOGA/COARE and TRMM, to validate the model diagnostics generated during assimilation against observed heating and hydrologic processes, and to include new information sources such as precipitation estimates, cloud observations, outgoing longwave radiation, and operational assimilation products and forecasts from

Instrument needs

Science Question Core Instruments	Ancillary	Contributing
1. *Atmospheric temperature and winds*		
AIRS + , LAWS, HIRDLS SWIRLS	Scatterometer CERES, SAGE III	MODIS-N, MISR/EOSP

2. *Hydrologic cycle*		
AIRS +, LAWS, Scatterometer Rain Radar	MIMR, TRMM	MODIS-N, CERES MISR/EOSP
3. *Atmospheric Chemistry*		
SAGE III, HIRDLS, TES MLS, SAFIRE, MOPITT	SWIRLS, LAWS AIRS +	
4. *Oceans and Surface Fluxes*		
Scatterometer, LAWS, AIRS +	MODIS-N	CERES

Orbit and other constraints

For purposes of validating model parameterizations of surface fluxes, cloud/radiation interactions, precipitation and planetary boundary layer depth, temporal sampling errors associated with the diurnal cycle are a major potential source of uncertainty. In addition, the growth of errors in assimilation products in unobserved regions also makes both morning and afternoon platforms with time offsets from European and Japanese instruments the preferred strategy. For the detection of climate change it is crucial that successive copies of the same instrument either be flown in nearly the same orbit, or if there is a time offset, that a substantial period (one annual cycle) of overlap be provided.

Recomendations to the payload panel

See Section IB.