APPLICATIONS OF ISES FOR THE ATMOSPHERIC SCIENCES

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Introduction

The proposed Information Sciences Experiment System (ISES) (Katzberg et al., paper in this CP) will offer the opportunity for real-time access to measurements acquired aboard the Earth Observation System (Eos) satellite. These measurements can then be transmitted to remotely located ground based stations. The purpose of this paper is to summarize a report on the application of such measurements to issues related to atmospheric science which was presented to a workshop convened to review possible application of the ISES in Earth sciences. It is noted that the initial report at the workshop and the present discussion are limited in scope and are not intended to be all inclusive of the applications that might benefit from ISES. Rather, the examples noted herein serve primarily to highlight that real-time access to some of the measurements currently proposed for the Eos could, indeed, benefit certain areas in atmospheric science.

The proposed protocol for Eos instruments requires that measurement results be available in a central data archive within 72 hours of acquiring data. Such a turnaround of raw satellite data to the final product will clearly enhance the timeliness of the results. Compared to the time that results from many current satellite programs, the 72-hour turnaround may be considered "real time". Nevertheless, the examples discussed below will emphasize applications in which a more rapid access to results will be required.

The need for rapid access to Eos results implies that there will be a real-time response to direct or change the course of an ongoing activity. An obvious and common example of the use of real-time data is meteorological data which is used directly (images) and indirectly (temperature and water vapor profiles) in daily forecasting. Data, such as visible and IR images from the various weather satellites (GOES, METOSAT, Polar Orbiter, etc.) are, in fact, often used as real-time data. This type of data is used for post mission and for flight and mission planning of many atmospheric chemistry experiments conducted today. It is difficult to imagine weather forecasting or field programs without real-time satellite data. There is, however, a limited experience base for applications of other types of real-time data from satellite platforms. This is a direct consequence of the lack of such data.

Examples of Current Atmospheric Chemistry Experiments

In this section, examples will be discussed showing how real-time measurements from one or more of the proposed Eos instruments could have been applied to the study of certain issues important to global atmospheric chemistry. Each of the examples discussed is based upon a field mission conducted during the past five years. Each of these examples will emphasize how real-time data could have been used to alter the course of a field experiment, thereby enhancing the scientific output. The centerpiece of each experiment was an aircraft instrumented to meet one or more specific objectives. For the examples, brief overviews of the scientific rationale and objectives(s), the region of operation, the measurements aboard the aircraft, and finally how one or more of the proposed Eos instruments could have provided data to enhance the productivity of the mission are discussed.

The first mission discussed here is the Amazon Boundary Layer Experiment (ABLE 2), which was conducted as part of NASA's Tropospheric Chemistry Program. It is of interest to note here that the initial impetus for this mission was based upon the global measurements of tropospheric carbon monoxide (CO) obtained from the first flight of the MAPS instrument aboard the shuttle (Reichle et al., 1986) in 1981. Figure 1 shows the global distribution of CO resulting from this shuttle flight. Note in particular, the enhanced CO mixing ratios appearing off the eastern coast of South America. The broad objectives of the ABLE 2 mission were to study the origin of this enhanced CO and the role of the Amazon Rain Forest in global chemistry/climate.

The Amazon Rain Forest is the world's largest remaining tropical rain forest. Figure 2 illustrates many of the processes that occur throughout the vast regions of the Amazon Basin. Both theoretical and available data support hypotheses that (1) tropical rain forest environments are characterized by relatively intense sources of certain biogenic gases (e.g., methane and nitrogen oxides) and aerosols; (2) the Amazon Basin is a region of frequent atmospheric instability with intense convective activity, resulting in the potential for rapid mixing of biogenic gases and aerosols to high altitudes where they impact global tropospheric chemistry; and (3) the tropical troposphere is a region of intense photochemical activity where oxidation of certain biogenic traces gases (e.g., isoprene (C_5H_8)) produces gaseous products, such as CO, that may be significant to global budgets.

The scientific objectives of ABLE 2 were accomplished through a coordinate program of measurements by U. S. and Brazilian scientists from ground, balloon, and airborne platforms. The centerpiece of the mission was instrumentation aboard the NASA Wallops Flight Facility Electra aircraft. During the mission, the Electra was based in Manaus, Brazil near the center of the Amazon Forest. The mission was conducted in two phases, the first at the beginning of the 1985 dry season during the June/July time period and the second at the close of the 1987 wet season during the April/May time period. The field operations during the 1987 rainy season were more extensive and are illustrated in Figure 3. Table 1 lists the investigators measurements during the 1987 missions. Similar measurements were also obtained during the 1985 mission. Figure 4 shows the study areas during the 1985 and 1987 operations. During both phases of ABLE 2, extensive airborne measurements were obtained over the rain forest including focused studies coordinated with the ground based instruments located approximately 50 km northwest of Manaus, basin scale surveys to characterize the source/sinks and photochemical transformation of trace species, and long range transport of primary and secondary tropospheric species.

As noted above, meteorological forecasting is a familiar example of the use of real-time satellite data. During ABLE 2 GOES, visible and IR images, received in Manaus via a communication link to the Langley Research Center Meteorological Center, proved invaluable for daily flight planning particularly during the convectively active rainy season. Frequently, images showing the meteorological conditions within a proposed study area several hours before initiating the particular flight plan were used for go/no-go decisions or for a change in flight plans. Similarly, real-time results from several of the proposed Eos instruments would have undoubtedly proved as useful for daily and long range flight planning. The availability of the large scale, upper tropospheric CO distributions, such as illustrated in Figure 1, would clearly have provided valuable insight into the temporal and spacial variability of large scale processes. Such CO data can be anticipated from the TRACER and/or MOPITT instruments proposed for Eos. During the 1985 dry season mission, dramatic increases in the background concentration of ozone (O_3), CO, and aerosols were observed. Highly structured layers containing enhanced concentrations of these species were frequently observed during several survey flights. The general increase in the background mixing ratios and the layers of air were attributed to long range transport of emission products associated with biomass burning occurring on the periphery of the forest several thousand kilometers from the ABLE 2 study regions. Real-time CO measurements from the TRACER or MOPITT instruments, O_3, aerosol measurements from the SAGE III instrument, and winds from the LAWS instrument would have provided advanced warning of the extent of these plumbs. Flight operations could have been re-structured to avoid these regions or to enhance the study within these regions. Furthermore, high resolution images from the IHRSS to provide information on the number and spacial extent of burning within or near the ABLE 2 study area would have also been useful.

The field deployment phase of another airborne study conducted by NASA's Tropospheric Chemistry Program was completed in September of 1989. This mission, denoted as CITE 3 (Chemical Instrument Test and Evaluation), focused on the study of the sulfur species in the marine environment. Unlike the ABLE 2 mission just discussed, the CITE 3 mission was totally airborne and conducted aboard the Wallops Flight Facility Electra. The primary objective of this mission was to evaluate the performance of instrumentation for measuring the sulfur compounds sulfur dioxide (SO_2), dimethelsulfide (DMS), hydrogen sulfide (H_2S), carbon disulfide (CS_2), and carbonyl sulfide (COS). A secondary objective of the mission was to determine, in a predominantly marine environment, the abundance and distribution of the above sulfur species which comprise the bulk of the gaseous global sulfur.

Atmospheric sulfur gas and aerosol species are involved in chemical processes which influence both air quality and climate. The primary sulfur species released into the atmosphere from anthropogenic, biogenic, and volcanic activity are the five compounds just noted above. Sulfur dioxide has both a large primary source in the form of fossil fuel combustion and a significant secondary source derived from the atmospheric oxidation of the sulfur precursor species CS_2, COS, H_2S, and DMS. Anthropogenic sources of SO_2 are currently estimated to account for approximately one half of the total global sulfur emissions.

Figure 5 illustrates what is currently thought to be the budget and important cycles for atmospheric sulfur. While the current budget estimates of the global sulfur budget are uncertain in part because of uncertainties associated with the measurement techniques, the most significant natural source of sulfur is thought to be associated with biogenic production of DMS by ocean phytoplankton. The lifetime of DMS is several hours. It is oxidized to SO_2 followed by further oxidation to sulfate aerosols which are a major source of cloud condensation nuclei in the marine environment. A particular relevant question associated with global sulfur is formation of Cloud Condensation Nuclei (CCN) and their role in climate control. It has been postulated that an increase in global temperature will initiate increased DMS emission leading to an increase in CCN's available for formation of clouds. This would act as a negative feedback on climate warming. An alternate argument is that there has been no evidence to suggest that the increases in ambient SO_2 during the last several decades associated with anthropogenic sources have not led to increased cloudiness and, therefore, the sulfur connection to global climate change should not be viewed as one which would reduce climate change.

The areas of operation during CITE 3 are shown on Figure 6. Tables 2a and 2b list the measurements aboard the aircraft during CITE 3. Integration and approximately half of the tests flights were conducted with the Electra aircraft based at the Wallops Flight Facility followed by a three week deployment to Natal, Brazil. Operations over the mid-Atlantic off the U.S. coast and over the tropical Atlantic ocean off the coast of Brazil provided a wide range of environmental conditions to test instrumentation and to study the sulfur budget. Note that in addition to the sulfur instrumentation under test (Table 2a), selected measurements of other species important for understanding the performance of the various sulfur instruments and/or the sulfur photochemistry were also included in the CITE 3 payload. (Table 2b).

The real-time output from three Eos instruments would have been particularly valuable during the CITE 3 mission. The MIRS and MODIS instruments would have provided a map of the phytoplankton concentration in upper layers of the ocean surface; and the LAWS instrument would have provided measurement of winds. As noted above, the biological output from certain phytoplankton species is the major source of DMS. Location of ocean regions that might have higher productivity of DMS would have provided for the first time a direct correlation of the emissions of DMS and its subsequent oxidation to SO_2. A direct measurement of tropospheric winds would have offered the opportunity to track a given air parcel and therefore study the photochemistry of DMS over at least one diurnal cycle. Attempts to study the photochemical history of a given air mass through the use of forward trajectory analysis have not met with a great deal of success, particularly in such data sparse regions as over the ocean. Real-time measurements of winds via LAWS should greatly improve the ability to repeat measurements in a given air parcel.

The Airborne Antarctic Ozone Hole Experiment (AAOE) and the Airborne Arctic Stratospheric Expedition (AASE), sponsored by NASA and NOAA to study the cause of the depletion of O_3 over the Antarctic continent and to evaluate the possibility of a similar phenomena over the Arctic regions, represent two airborne missions focused on stratospheric chemistry. Both missions utilized the NASA DC-8 and ER-2 aircrafts instrumented for measurements of a range of species (Table 3) pertinent to the chemistry of stratospheric O_3. The scientific rationales for these missions have been well publicized in the press and scientific literature and therefore will not be discussed here. It is only noted here that these expeditions were also based upon satellite observations from TOMS O_3 first showing the reduction in O_3 over the Antarctic continent. A number of the instruments proposed for Eos would have provided valuable inputs to the operation of these missions. In particular, upper tropospheric and stratospheric measurements of O_3, temperature, water vapor, nitrogen dioxide, and stratospheric winds via proposed Eos instruments such as the Dynamic Limb Sounder (DLS), High Resolution Research Limb Sounder (HIRRLS), Microwave Limb Sounder (MLS), Spectroscopy Atmosphere Far-IR (SAFIRE), and Stratospheric Wind Infrar Limb Sounder (SWIRLS).

Examples of Future Field Studies in Atmospheric Chemistry

In this section several specific examples of airborne atmospheric chemistry experiments that are currently in the planning stages are briefly discussed. Here again, it is recognized that these examples are a rather limited subset of the field experiments that are in various stages of planning by U.S. and foreign agencies. The intent here is primarily to emphasize the obvious - namely, that future airborne atmospheric science missions will exist, and that as they grow in size and complexity, the availability of real-time Eos measurements can be expected to become an integral part of each mission.

A particularly relevant mission for consideration here is, like several of the missions discussed above, based upon global measurements of an important trace atmospheric species from a satellite platform. This proposed mission will study the chemical and dynamic processes that contribute to the formation of a large scale O_3 enhancement over the tropical Atlantic Ocean west of central Africa (Figure 7). This feature was derived from analysis of TOMS and SAGE II observations (Fishman, 1990). This feature, seasonal in nature with its maxima occurring during the September to November time period, represents a significant enhancement to the tropical ozone climatology and is undoubtedly important to understanding the current global O_3 budget and the global distribution of the hydroxyl radical, the most important species in tropospheric photochemistry.

The proposed mission (e.g., TRACE-A) will focus on the origin of this O_3 enhancement which has been identified in satellite observations as a common but variable feature during this period. Ozonesonde measurements from Natal, Brazil have also noted a similar O_3 enhancement during this same time period. It is hypothesized that regional scale dynamic and chemical conditions result in photochemical production of O_3 in mid-tropospheric air which has been enriched in nitrogen oxides from continental surfaces sources such as biomass burning in central Africa.

A series of aircraft flight, satellite observations, and ground-based support measurements have been proposed to elucidate the dynamical and chemical factors determining the origin of this newly discovered component in the global tropospheric O_3 budget. It is anticipated that measurement capabilities will be required for N_xO_y, HNO_3, PAN, NMHC, CO, O_3 , and aerosol composition and distribution. The current planning for the operational area for the TRACE-A mission is shown in Figure 6. The O_3 enhancements appear to be predominately in the free troposphere and to extend over a vast area of the tropical Atlantic and will therefore require the use of NASA's newly acquired DC-8 aircraft.

It is anticipated that the aircraft measurements during the TRACE-A mission will be coordinated with real-time satellite measurements of O_3 from current satellite instruments such as the TOMS and SAGE II whenever possible. The availability of real-time profiles of O_3 from the Eos SAGE III instrument would clearly make a valuable contribution during the proposed study. Similarly, real-time data on the distribution of CO from the TRACER and/or MOPITT instruments, and upper tropospheric profiles of H_2O and aerosols from SAGE III would enhance the ability to conduct this mission. Such measurements would define the temporal and spacial extent of the O_3, thereby providing real-time input to the flight planning to enhance the scientific output from this mission. Finally, a particularly valuable Eos measurement would be real-time upper tropospheric winds from the LAWS instrument. As noted above, these data would provide the unique ability to track an air parcel and study the photochemical formation of O_3 within the same parcel over a period of several days. Such measurements would be useful in determining if the enhanced O_3, indeed originates from the photochemistry of biomass emissions.

A series of airborne missions that will focus on studying transport and photochemistry of key trace tropospheric species over the Pacific Ocean is also under consideration. (See Fig. 6.) It is anticipated that these missions will begin in the early 1990's with perhaps three to four major field operations over a period of four to five years. Satellite measurements over the vast expanse of the Pacific Basin can provide invaluable support to these missions. Particularly useful would be measurements of upper tropospheric winds via the LAWS instrument since this region is almost devoid of rawinsonde measurements. Real-time winds along with measurements of other trace species such as CO and O_3 would also be valuable for defining the transport of effluent to the Pacific basin from the Asian continent. Measurement of CO, O_3 and H_2O would be important in assessing the origin of the air masses. Volumes of air having low CO and

H_2O and high O_3, for example, are likely to have a significant contribution from stratospheric regions. Air masses having high CO and H_2O are likely to have a significant contribution from the marine boundary contaminated by an anthropogenic source.

Concluding Remarks

The examples discussed above illustrate possible applications of real-time Eos data that could be made available through the ISES. Each example was based upon a field mission in which aircraft flight planning would actively respond to global/regional satellite observations. In each case, it was assumed that Eos observations provided a large scale map of the spacial and temporal distributions of one or more key atmospheric parameters of species. This map was then used to direct a more detailed study via an instrumented aircraft.

As the International Geosphere Biosphere Program (IGBP) gains momentum in the 1990's, multi-nation field experiments employing ground- and aircraft-based measurement platforms can be expected. These field programs will be global in scope and, undoubtedly, will be designed to take advantage of the global coverage offered by satellite observations. It seems clear that, as with real-time meteorological data, real-time observations of trace atmospheric species will become an invaluable tool for these missions in the 1990's and beyond.

References

1 Reichle, H. G., V. S. Connors, J. A. Holland, W. D. Hypes, H. A. Walleo, J. C. Casas, B. B. Gormsen, M. S. Saylor, and W. D. Hesketh: "Middle and Upper Tropospheric Carbon Monoxide Mixing-Ratios as Measured by a Satellite-Borne Remote Sensor During November 1981," J.G.R., vol. 91, 1986, pp. 10865–10887.

2. Toon, Owen B., James F. Kasting, Richard P. Turco, and May S. Liu: "The Sulfur Cycle in the Marine Atmospheric," J.G.R., vol. 92, 1987, pp. 943-963.

3. Fishman, Jack, Catherine E. Watson, Jack C. Larsen, and Jennifer A. Logan: "Distribution of Tropospheric Ozone Determined From Satellite Data," J.G.R., vol. 95, March 20, 1990, pp. 3599–3617.

Table 1. Principal Investigators in ABLE-2B Field Expedition April–May 1987

INVESTIGATOR	INSTITUTION	INVESTIGATION
	UNITED STATES PRINCIPAL INVESTIGATORS	
Meinrat O. Andreae	Florida State University	Sulfur measurements (a,s)
Sherwin M. Beck	NASA Langley Research Center	Airborne meteorological data (a)
Edward V. Browell	NASA Langley Research Center	Aerosols, ozone profiles (a)
David R. Fitzjarrald	State University of New York at Albany	Meteorological studies (s)
Michael Garstang	University of Virginia	Meteorological studies (s)
Gerald L. Gregory	NASA Langley Research Center	Ozone (a)
Robert C. Harriss +	NASA Langley Research Center	Methane (s), carbon dioxide (a)
Charles L. Martin	Simpson Weather Associates	Meteorological studies (s)
Pamela A. Matson ‡	NASA Ames Research Center	Nitrous oxide (s)
Reinhold A. Rasmussen	Oregon Graduate Center	Isoprene/other trace gases (a,s)
John A. Ritter	NASA Langley Research Center	Flux of carbon monoxide, ozone, water vapor (a)
Jeffrey E. Richey ‡	University of Washington	Methane, carbon dioxide (r)
Glen W. Sachse	NASA Langley Research Center	Carbon monoxide (a)
Hanwant B. Singh	NASA Ames Research Center	PAN (a)
Robert W. Talbot	NASA Langley Research Center	Aerosols (a)
Arnold L. Torres	NASA GSFC Wallops Flight Facility	Nitric oxide (a)
Peter Vitousek ‡	Stanford University	Nitrous oxide (s)
Steven C. Wofsy	Harvard University	Nitric oxide (s), carbon dioxide (a,s)
	BRAZILIAN PRINCIPAL INVESTIGATORS	
Elen M. C. Cutrim	Federal University of Para	Rainfall studies (s)
Pedro L. S. Dias	University of Sao Paulo	Meteorological studies (s)
Volker W. J. H. Kirchhoff	Instituto de Pesquisas Espaciais	Ozone, Carbon monoxide (s)
Luiz C. B. Molion	Instituto de Pesquisas Espaciais	Project Scientist – Brazil (s)
Paulo Artaxo Netto	University of Sao Paulo	Aerosols (a, s)
Carlos A. Nobre	Instituto de Pesquisas Espaciais	Meteorological studies (s)
Daniel Nordeman	Instituto de Pesquisas Espaciais	Radon (a)
Lycia M. Moreira-Nordemann	Instituto de Pesquisas Espaciais	Precipitation chemistry (s)
Alberto W. Setzer	University of Sao Paulo	Satellite imagery (s)

+ ABLE 2B and AGE Program ‡ AGE Program (a) Airborne (s) Surface (r) River

Table 2a. Sulfur Measurements During CITE-3 Field Expedition, August–September 1989

TECHNIQUE		ANALYSIS[1]	SPECIES					ORGANIZATION	INVESTIGATOR
CT/GC/FPD	Analysis Opt. 1	IFA	SO_2	—	—	—	—	Drexel University	D. C. Thornton
	Analysis Opt. 2	IFA	—	—	H_2S	—	OCS		
	Analysis Opt. 3	IFA	—	DMS	—	—	—		
	Analysis Opt. 4	IFA	—	—	—	CS_2	—		
CT/GC/MS/ILS	Analysis Opt. 1	IFA	SO_2	DMS	—	CS_2	—	Drexel University	A. R. Bandy
	Analysis Opt. 2	IFA	—	—	—	—	OCS		
GC/IF/ECD (w/scrubber)		IFA	—	DMS	—	—	—	National Oceanic and Atmospheric Administration/ Pacific Marine Environmental Laboratory	J. E. Johnson
GC/IF/ECD (w/out scrubber)			—	—	—	CS_2	OCS		
GWA/GC/FPD		PFA	—	DMS	—	—	—	Max Planck Institute for Chemistry	M. O. Andreae
NATUSCH		PFA	—	—	H_2S	—	—		
CT/GC/FPD		IFA	—	DMS	—	—	—	University of Miami	E. S. Saltzman
NATUSCH		PFA	—	—	H_2S	—	—		
GWA/GC/FPD		PMA	—	DMS	—	—	—	University of Washington	R. J. Ferek
FC/IC		PMA	SO_2	—	—	—	—		
CHEMILUMINESCENCE (Filter)		PFA	SO_2	—	—	—	—	Institut fur Meteorologie und Geophysik	H. -W. Georgii
	(Continuous)	IFA	SO_2	—	—	—	—		

[1]IFA - In-Flight Analysis
PFA - Post-Flight Analysis
PMA - Post-Mission Analysis

Table 2b. Ancillary Measurements During CITE-3 Mission

PRINCIPAL INVESTIGATOR	INSTITUTION	SPECIES
Enio Periera	Instituto de Pesquisas Espaciais	Radon
Paulo Artaxo	University of Sao Paulo	Aerosol Trace Elements
Gerald Gregory	NASA/Langley	O_3, Aerosol Size Distribution
Glen Sachse	NASA/Langley	CO
Sherry Farwell	University of Idaho	Total Sulfur
John Bradshaw	Georgia Institute of Technology	NO, NO_2, NO_y
Ronald Ferek	University of Washington	Aerosol Composition, MSA, CN
Patricia Matral	University of Miami	Ocean Productivity
GTE Project	NASA/Langley	Aircraft Met./ Position/ Met. Forecasting/UV Flux/ Sea State

Table 3. Measurements and Platforms During Antarctic Ozone Hole Experiment

Investigator and Affiliation *	Species	Type of Measurement
Anderson (Harvard)	ClO, BrO	local ER-2
Wahner (NOAA AL)	OClO, BrO, O_3, NO_2	column DC-8
Farmer (JPL)	$ClONO_2$, HCl, O_3, NO, NO_2, HNO_3, H_2O	column DC-8
Mankin/Coffey (NCAR)	O_3, NO, NO_2, HNO_3, H_2O	column DC-8
Browell (NASA Langley)	O_3, Aerosols	profile DC-8
Gregory (NASA Langley)	O_3	local DC-8
Proffitt (NOAA AL)	O_3	local ER-2
Starr (NASA Ames)	O_3	local ER-2
Fahey (NOAA AL)	NO or NO_y	local ER-2
Wilson (DU)	aerosol, condensation, nuclei	local ER-2
Ferry (NASA Ames)	aerosol	local ER-2
Gandrud (NCAR)	NO_3	local ER-2
Kelly (NOAA AL)	H_2O vapor or total H_2O	local ER-2
Oberbeck/Pueschel (NASA Ames)	chemical composition vertical profile ~ 1μm	profile DC-8
Loewenstein (NASA Ames)	N_2O	local ER-2
Heidt/Vedder (NCAR/ NASA Ames)	whole air CH_4, N_2O, CO, CFCs	local ER-2/DC-8
Chan (NASA Ames)	*U, V, W, T, p* †	local ER-2
Gary (JPL)	$\delta T/\delta p$ †	local ER-2
Loewenstein (NASA Ames)	N_2O	local ER-2

* AL, Aeronomy Laboratory; JPL, Jet Propulsion Laboratory; NCAR, National Center for Atmospheric Research; DU, Denver University.

† *U*, eastward wind; *V*, northward wind; *W*, vertical wind; *T*, temperature; *p*, pressure

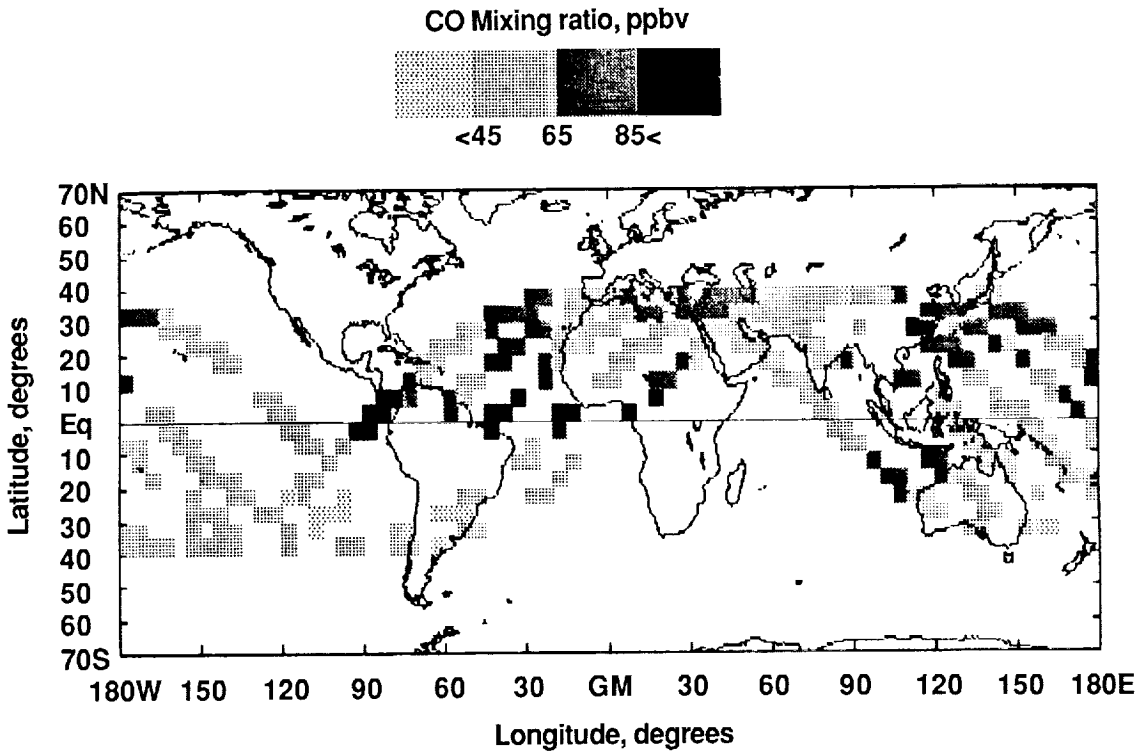
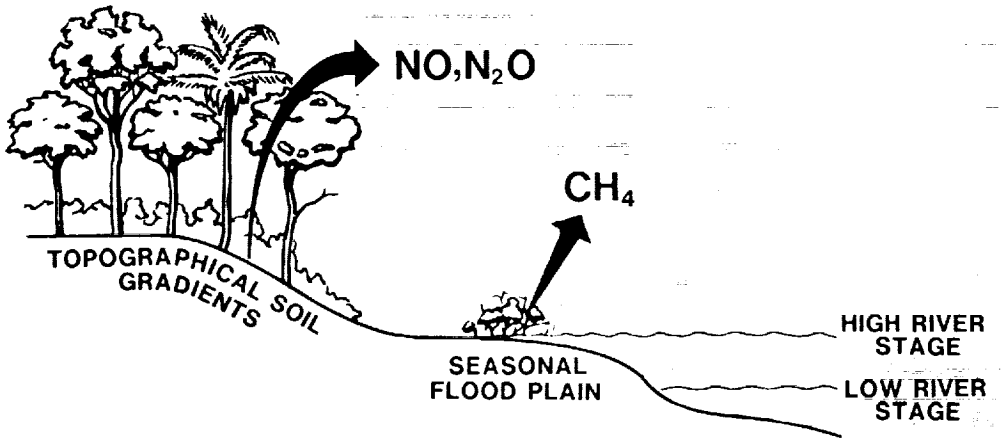


Figure 1. Tropospheric carbon monoxide mixing ratio MAPS experiment, 14 November 1981.

TRACE GAS EXCHANGE PROCESS IN THE TROPICAL RAIN FOREST

- SOILS ARE THE DOMINATE SOURCE FOR CH_4, NO, & N_2O



TRACE GAS EXCHANGE PROCESS IN THE TROPICAL RAIN FOREST

- THE FOREST CANOPY IS A DOMINATE SOURCE/SINK FOR H_2O, CO_2, O_3,& C_5H_8

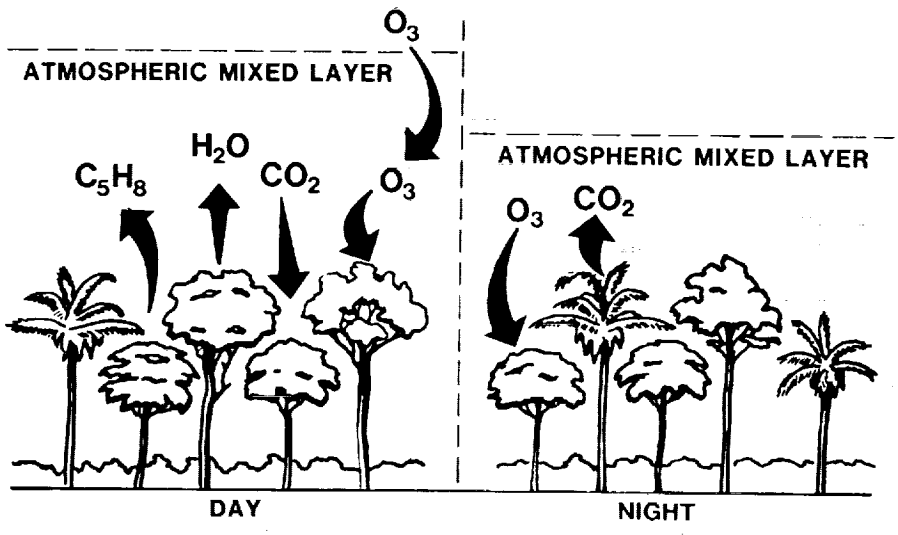


Figure 2. Trace gas exchange processes in the tropical rain forest. (a) Tropical soils are a significant source of methane (CH_4), nitric oxide (NO), and nitrous oxide (N_2O). (b) The forest canopy is a dominant source/sink for water (H_2O), carbon dioxide (CO_2), ozone (O_3), and isoprene (C_5H_8).

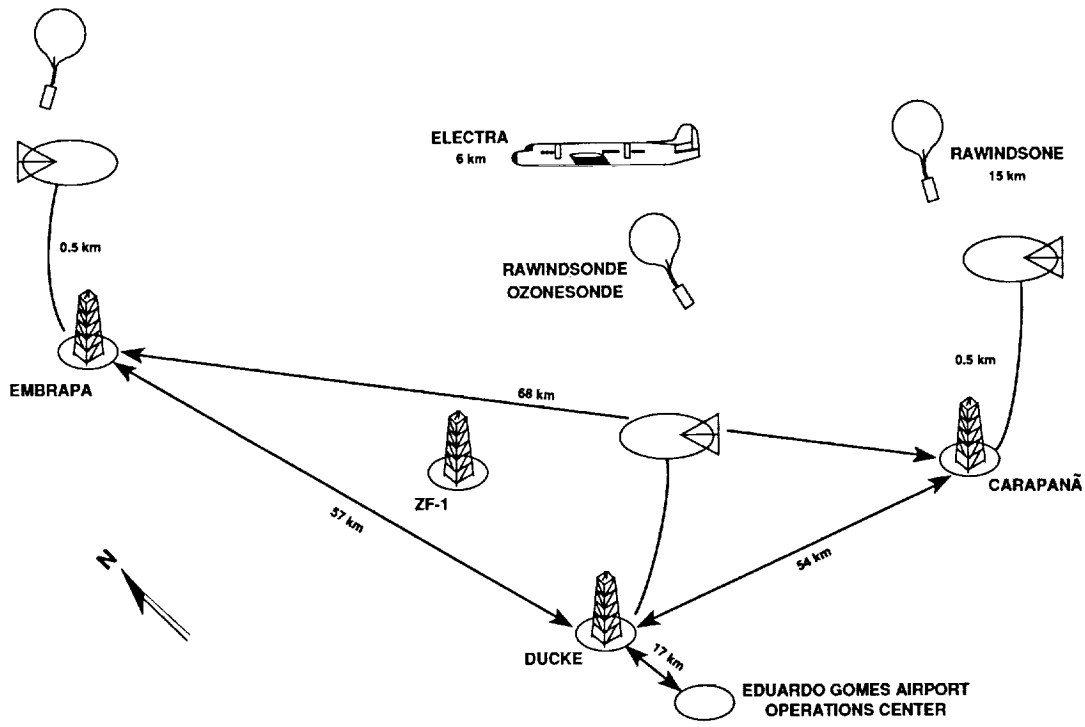
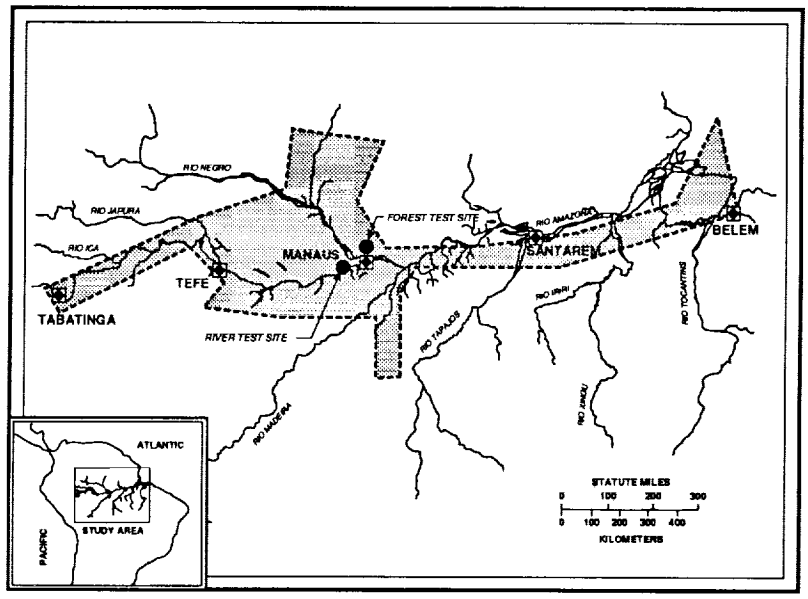
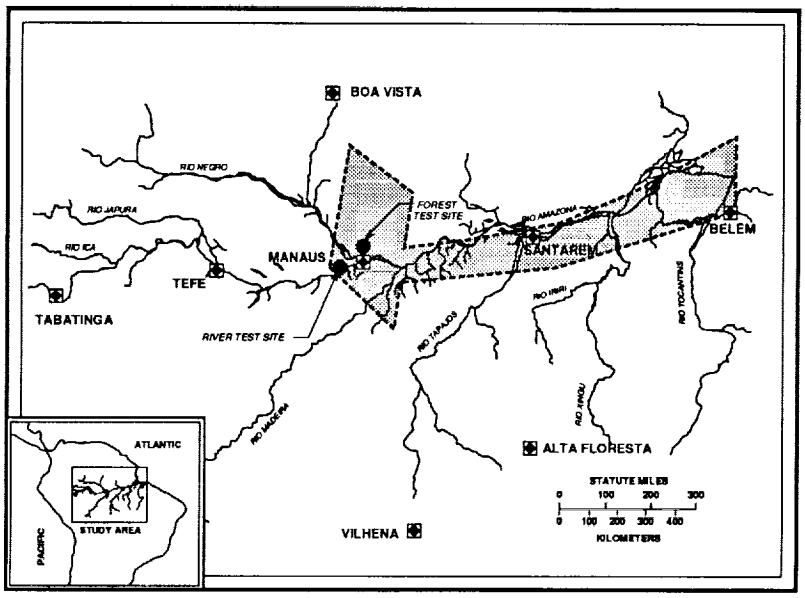


Figure 3. Mesoscale Convective Complex Triangle (MCCT) with ground and airborne sensor platforms deployed during the ABLE-2, 1987 Wet Season Mission. During the 1985 dry season, ground measurements were concentrated at the Ducke site.



(a)



(b)

Figure 4. Map of research areas for (a) ABLE-2A and (b) ABLE-2B.

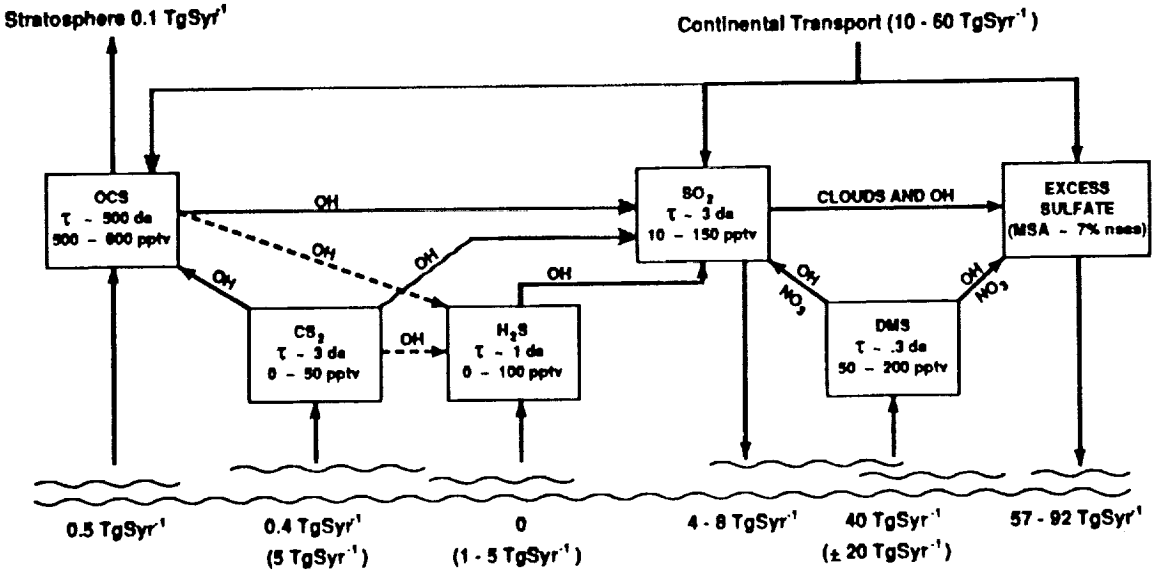


Figure 5. Schematic of marine sulfur cycle (modified from Toon et al., JGR, 92, 1987).

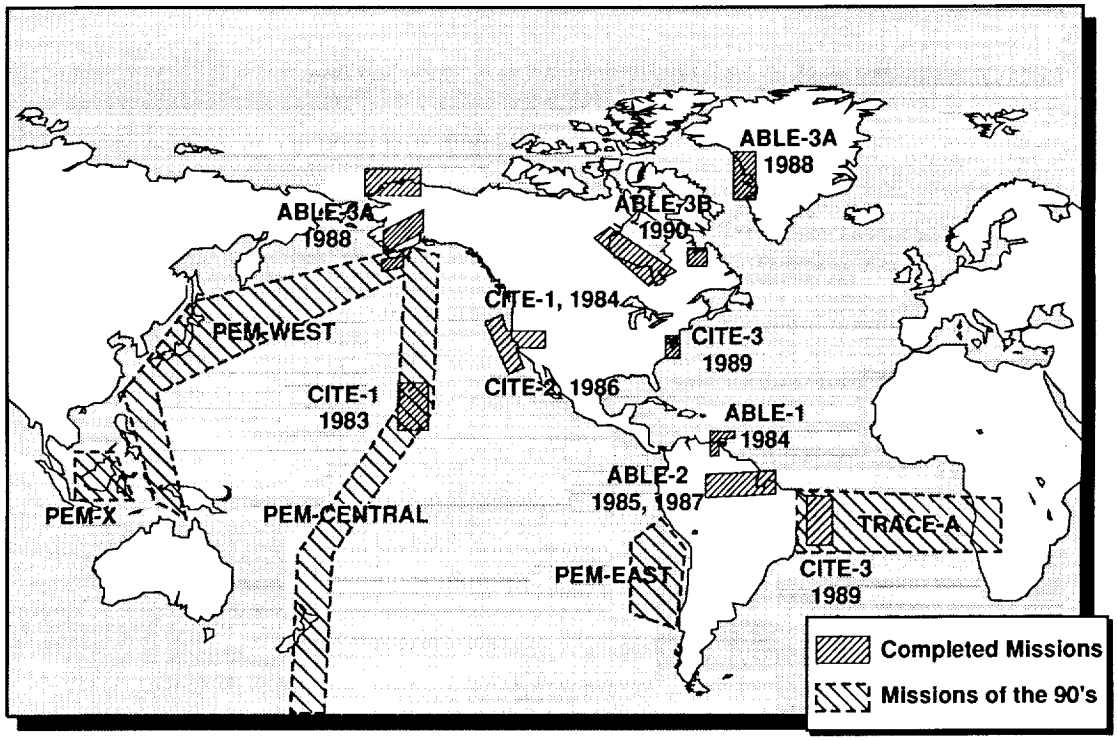


Figure 6. Completed and potential mission sites of the Global Tropospheric Experiment. The completed missions include CITE-1, -2, -3 and ABLE-1, -2, -3. Missions that may be conducted in the 1990's include TRACE-A, PEM-West, -Central, -East, and -X.

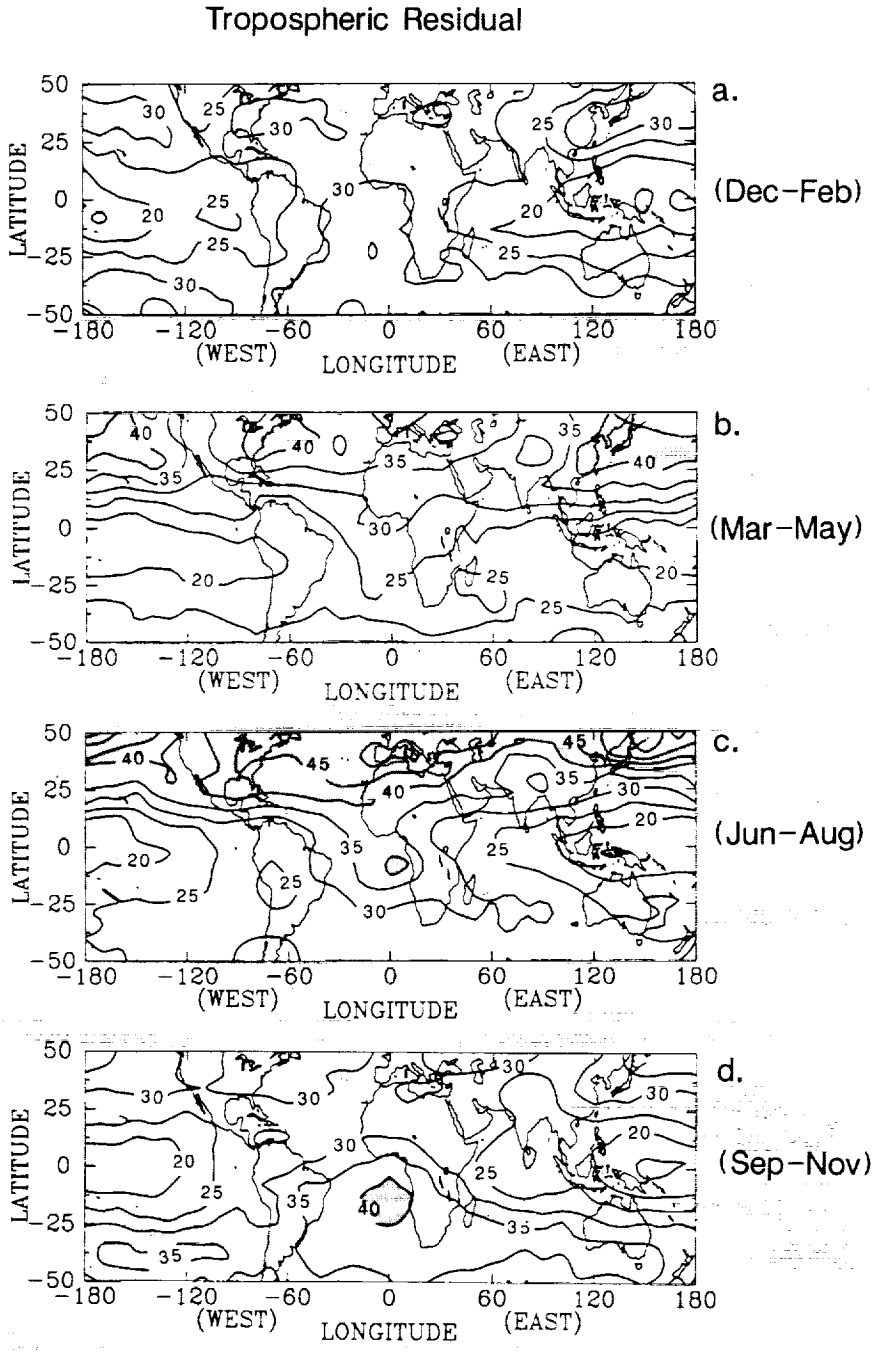


Figure 7. Seasonal contours of global tropospheric ozone derived from satellite observations. Note ozone enhancement in south Atlantic Ocean off coast of Africa in September–November time period. (Figure provided by Jack Fishman, Langley Research Center.)