Appendix A: Research and The Earth Observing System

Until recently, meteorological applications were the primary force behind the development of civilian remote sensing systems. In the future, meteorology *and* global change research will influence the direction of remote sensing developments. Widespread attention to scientific issues regarding global change is likely to result in spending several billion dollars for sensor and spacecraft development. This appendix evaluates the relationship between planned sensors and the study of climate and environment, and reviews sensor development plans in detail,

Future remote sensing systems will provide improved recognition and understanding of environmental problems, and collect data to inform scientists and policymakers of the ramifications of a changing environment.[1] Future systems (such as EOS) are designed to provide a better understanding of the processes **affected by** changes in the atmosphere.[2] More complete data from remote sensing satellites, combined with increased opportunities to test models against reality, can improve environmental models, especially general circulation models (GCMS) of global climate.[3]

Remote sensing from space provides an effective way to determine the extent of environmental change. Space-based remote sensors are capable of yielding the synoptic view of global events necessary to identify and quantify changes occurring in the atmosphere and on the

I In addition to helping to answer questions about whether the Climate is changing, remote sensing systems are regularly used to monitor ecosystems, map wetlands, and track pollution.

2 NASA's EOS program is being designed to address many of the key areas of scientific uncertainty. See the National Research Council, *The U.S. Global Change Research Program, An Assessment of FY 1991 Plans,* National Academy Press, 1990. Although EOS has been restructured since this evaluation was written most of the instruments evaluated by the study are still included in EOS.

3 Effectiveness of the data from any observation system in explaining observed phenomena is determined by the way data are used.

Box A-1-Climate Change

Many oft he remote sensing systems discussed in this report are designed to provide data about the climate. The Earth's climate is determined by many factors. The primary force is radiant energy from the Sun, and the reflection or absorption and reradiation of this energy by atmospheric gas molecules, clouds, and the surface of the Earth itself (including forests, mountains, ice sheets, and urban areas). A portion of the reradiated energy leaves the atmosphere. Over the long term, balance is maintained between the solar energy entering the atmosphere and energy leaving it. Within this balance, interactions among the atmosphere, snow and ice, oceans, biomass, and land cause variations in global and local climate. For example, El Nino, the large-scale warming of the tropical Pacific that occurs periodically, is apparently the result of complex interactions between the ocean and atmosphere.'

A region's general climate is defined by aggregate weather patterns-for example, snowfall, predominant wind direction, summertime high temperature, precipitation-averaged over several decades or longer. These patterns can vary substantially from one year to another in a given area. The mean annual temperature of the United States, for example, can differ by O.5 to 1.5 ^{0}C. When scientists discuss climate *change,* they are generally referring to trends that persist for decades or even centuries, over and above natural seasonal and annual fluctuations. One type of change arises from forces that are external to the Earth's climate system. The ice ages and glacial-interglacial cycles, for example, are thought to have been triggered by changes in the seasonal and geographical distributions of solar energy entering the Earth's atmosphere associated with asymmetries in the Earth's orbit around the Sun. Also, major volcanic eruptions can deposit aerosols (e.g., sulfate particles) into the stratosphere, partially blocking or screening sunlight from reaching the surface of the Earth and thus temporarily cooling the Earth's surface. Variations in volcanic activity (1992 was cooler than normal in many parts of North America, in all likelihood because of the eruptions of Mt. Pinatubo), ice sheets, forest cover, marine phytoplankton populations, and/or ocean circulation, among other factors, may have interacted with solar variability (including changes in the Sun's brightness) to determine the Earth's past temperature record.[2]

Other changes to the climate can be linked to human activity. Fossil fuel emissions and the release of compounds such as chlorofluorocarbons have changed the makeup of the atmosphere. To what extent human *activity has contributed to changes in* atmosphere and how these changes affect the climate is not clear.

1 G.A. Meehl, "Seasonal Cycle Forcing of El Niño—Southern Oscillation in a Global Coupled Ocean-Atmosphere GCM," *Journal of Climate* 3:72-98, 1990.

2 See s. Baliunas, and R, Jastrow, "Evidence for Long-Twin Brightness Changes of Solar-Type Stars," *Nature* 348:520-522, 1990; W.S. Broecker, "Unpleasant Surprises in the Greenhouse?" *Nature* 328:123-126, 1987; R.A. Bryson, "Late Quarternary Volcanic Modulation of Milankovitch Climate Forcing," *Theoretical and Applied Climatology* 39:115-125, *1989,*

SOURCE: Adapted From U.S. Congress, Office of Technology Assessment, *Changing by Degrees: Steps to Reduce Greenhouse Gases,* OTA-O-482 (Washington, DC: U.S. Government Printing Office, February 1991).

surface. Global viewing is critical to understanding geophysical processes, since many seemingly isolated events are parts of a whole. As a result of growing catalogues of data, better quantitative models that simultaneously consider ocean and atmosphere have grown in sophistication.[4]

Remote Sensing and the Current State of Climate Research

Is there evidence of climate change (box A-l)? What are the implications of variations in temperature, rainfall, cloud cover, polar ice and sea level? These questions spark controversy among climatologists, biologists, economists, and politicians. Differences in

[4] Thomas F. Malone, "Mission to Planet Earth,'' *Environment,* vol. *28,* October *1986,* p.6.

opinion often derive from large uncertainties in data, imperfect numerical models, and assumptions that drive predictive models. For example, climate data show evidence of a slow but steady increase in global temperature, and glacial records indicate higher levels of CO_2 and other gases than at any other time since the ice age, Yet future trends and consequences of continued climate and environmental change are highly uncertain. Remote sensing systems are essential if researchers are to assemble a comprehensive picture of global processes.

The study of global change, much like the study of meteorology, encompasses the effects of many earth processes.[5] Scientific uncertainty manifests itself as wide variations in general circulation models used to predict climate change and understand the human impact on the environment. Key elements of uncertainty in developing predictive models include:

- clouds, primarily cloud formation, dissipation, and radiative properties, which influence the response of the atmosphere to greenhouse forcing;
- **oceans,** the exchange of energy between the ocean and the atmosphere, between the upper layers of the ocean and the deep ocean, and transport within the ocean, all of which control the rate of global change and the patterns of regional change;
- **greenhouse gases,** quantification of the uptake and release of the greenhouse gases, their chemical reactions in the atmosphere, and how these may be influenced by climate change; and
- **polar ice sheets,** which affect sea level rise.[6]

General circulation models are complex computer models of the climate system that quantify the interaction of various elements of the environment, allowing researchers to develop hypotheses regarding the climate and elements of change. Uncertainties in GCMS can be reduced in two ways: first, improve the data used in GCMS; second, rigorously test predicted results against real events to improve the models themselves.

Plans for future remote sensing satellite systems call for the development of a number of sensors to obtain data that will improve scientists' understanding of clouds, oceans, and atmosphere. These data, which will be used in GCMS and other models, should improve the ability of scientists to understand the interaction of systems and reduce some of the current uncertainty.[7]

Uncertainties regarding climate change abound, yet substantial evidence exists that environmental change has already taken place. According to many climatologists, human activity is altering the climate system beyond the limits of natural rates of change experienced by the Earth over the last hundreds of thousands of years.[8] Human activity is dramatically changing the chemical makeup of the Earth's atmosphere. Atmospheric concentrations of several "greenhouse gases, ' which trap heat in the atmosphere, naturally keeping the earth at a habitable temperature, have risen rapidly over the last 100 years, (box A-2) and according to some, have contributed to increased average temperatures.[9] Most of these gases (carbon dioxide, methane, and nitrous oxide) occur naturally, but their rapid increase results mainly from human activity. For example, the atmospheric concentration of carbon dioxide is currently increasing about 30 to 100 times faster than the rate of natural fluctuations found in ice

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[5] Ibid, p. 6.

[6] Intergovernmental Panel on Climate Change, *Scientific Assessment of Climate Change,* World Meteorological Organization, 1990, p. xxxi.

[7] Data detailing changes in land surface hydrology, solar radiation cycle, characteristics of surface albedo, the role of atmospheric and surface winds, amount and health of biomass, and changes in land features will also play a large role in understanding climate and environmental change.

[8] R.A. Berner, ' 'Atmospheric Carbon Dioxide Levels Over Phanerozoic Time, ' Science 249: 1382-1386, 1990; IPCC, op. cit.; C. Lorius, et al., "The Ice-Core Record: Climate Sensitivity and Future Greenhouse Warming, " *Nature* 347: 139-145, 1990.

[9] According to climate models in use today, increases of 0.3 to 1.1 C should have occurred over the past 100 years as a result of increased atmospheric concentrations of greenhouse gases. Natural climate variability and other factors (measurement errors, urban heat island effects, etc.) confound detection of almost any climate trends, however. The Intergovernmental Panel on Climate Change, or IPCC—a group of several hundred scientists from 25 countries, described below-concluded that the global temperature record over this period indicates that the Earth actually has warmed by about 0.45 C, which is within the range of estimates. Yet the findings of the WCC, while representing the views of many atmospheric scientists, are not universally accepted.

Box A-2-Global Warming and the Greenhouse Effect

Emissions of greenhouse gases constitute a new force for climate research (in addition to the natural climatic phenomena). Because of natural variability in climate, the IPCC concluded that the observed 20th-century warming trend would have to continue for one to two more decades before it can be unambiguously attributed to enhanced greenhouse gases.'

About 30 percent of the solar radiation reaching the Earth is reflected by the atmosphere and Earth back to space, and the remainder is absorbed by the atmosphere, ice, oceans, land, and biomass of Earth. The Earth then emits long-wave radiation in the infrared and microwave wavelengths, which is partially absorbed and 'trapped" by atmospheric gases.[2] The result of these natural processes is the "greenhouse" effect- warming of the Earth's atmosphere and surface. Without the natural heat trap of these atmospheric gases, Earth's surface temperatures would be about 33 °C (60 °F) coder than present.[3] Human activities during the last century have resulted in substantial increases in the atmospheric concentrations of $C0_2$, CH_4, and N_20.[4] As concentrations of these gases increase, more radiation should be trapped to warm the Earth's surface and atmosphere. However, as more heat is trapped and the Earth and atmosphere warm, more thermal radiation should be emitted back to space, eventually restoring the energy balance or equilibrium, but leaving a warmer climate.[5]

The basic "heat trapping" property of greenhouse gases is essentially undisputed. However, considerable scientific uncertainty remains about how and when Earth's climate will respond to enhanced greenhouse gases. The more uncertain aspects of climate response include: climate feedbacks that will help determine the ultimate magnitude of temperature change (i.e., "equilibrium" warming); the role of the **oceans in setting the pace of warming; and other climate changes that might** accompany warming and how specific regions of the world might be affected. Planned remote sensing systems such as the Earth Observing System platforms will carry sensors that will measure these aspects of climate variability.

Predictions of future warming are highly uncertain, because of the inaccuracies of climate models themselves and varying projections for future greenhouse gas emissions levels. Future emissions will be tied to population and economic growth, technological developments, and government policies, all of which are difficult to project.

To avoid the pitfalls and complexity of estimating future emissions, and to provide a common basis for comparing different models or assumptions, climate modelers typically examine climates associated with preindustrial levels of atmospheric $C0_2$ concentration. These are compared to "equilibrium" climate- i.e., when

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1 Intergovernmental Panel on Global Change, *Scientific Assessment of Climate Change,* World Meteorological Organization, 1990.

2 See: Dickinson, R.E. and R.J. Cicerone, "Future Global Warming From Atmospheric Trace Gases," *Nature* 319:109-115, 1936; Lindzen, R. S., "Some Coolness Concerning Global Warming," *Bulletin of the American Meteorological Society* 71:288-290, 1990.

3 At 60 °F (33 °C) cooler than at present, life as we know it today on Earth would not be possible. Water vapor (in the form of clouds) and carbon dioxide (CO_2) are the major contributors to this effect, with smaller but still significant contributions from other trace gases, such as methane (CH_4), nitrous oxide (N_2O), and ozone (O_3).

4 One must also consider the introduction and rapid increase of the synthetic chlorofluorocarbons (CFCs), which contribute to the destruction of atmospheric ozone (03), which absorbs incoming ultraviolet radiation >320 nm. Without this "filter," we will see an increase in Illness and habitat destruction due to ultraviolet energy.

5 The uncertainty of warming forecasts Is twofold: how much warming will occur; and what happens after small amounts of warming? The first is self-explanatory, the second a captivating scientific debate. Will Increased temperatures cause more suspended water vapor (clouds) reflecting more energy and restoring current temperatures? Will severe storms become more common?

the climate system has fully responded and is in equilibrium with a given level of radiative forcing[6] associated with double those levels. Although such "sensitivity analyses" provide useful benchmarks, they are unrealistic in that they *instantaneously* double CO_2 concentrations, rather than increase them gradually overtime. In the last few years, scientists have intensified research using more realistic "transient" climate models where CO_2 increases incrementally over time.[7]

Many models indicate that a range of 1.5 to 4.5 °C (3 to 8 oF) bounds the anticipated equilibrium warming, likely in response to a doubling of CO_2 from preindustrial levels.[8] Uncertainty about the actual figure is primarily due to uncertainty about feedbacks-processes that occur in response to initial warming and act either to amplify or dampen the ultimate equilibrium response. The lower end of the range (1.5 °C change) roughly corresponds to the direct impact of heat trapping associated with doubled CO_2, with little amplification from feedbacks. The upper end of the range (4.5 'C) accounts for feedback processes that roughly triple the direct heat-trapping effect. Hypothesized feedbacks that could release extra CH_4 and CO_2 into the atmosphere are not included in present models,[9] so warming could be even more severe. On the other hand, clouds may block much more solar radiation than models presently assume and thereby reduce the warming.

A 1.5 to 4.5 'C warming bounds model predictions of warming in response to this reference or benchmark CO_2 level. Higher or lower CO_2 concentrations (or a combination of greenhouse gas levels) might lead to greater or less warming. The I PCC "business as usual" emissions scenario projects a global mean temperature increase above today's level of about .25'C (0.54 oF) per decade, or an increase of roughly 1.0'C (2.2 'F) by 2030 and 3.1 "C (6.6 "F) by 2100.

6 Change in temperature or climate caused by changes in solar radiation levels.

7 IPCC; Washington, W.M. and G.A. Meehl, "Climate Sensitivity Due to Increased CO_2: Expedients With A Coupled Atmosphere and Ocean General Circulation Model," *Climate Dynamics* 4:1 38, 1989.

8 IPCC; Stouffer, R.J., S. Manabe, and J. Bryan, "Interhemispheric Asymmetry in Climate Response to a Gradual Increase of Atmospheric Carbon Dioxide," *Nature* 342:660-662, 1989; J. Hansen et al., "Global Climate Changes as Forecast by the Goddard institute for Space Studies Three-Dimensional Model," *J. Geophysical Research*, 93:9341 -9364, 1988.

9 IPCC; Lashof, D., "The Dynamic Greenhouse: Feedback Processes that May Influence Future Concentrations of Atmospheric Trace Gases and Climatic Change," *Climatic Change* 14:213-242, 1989.

SOURCE: Adapted from U.S. Congress, Office of Technology Assessment, *Changing by Degrees: Steps to Reduce Greenhouse Gases* (Washington, DC: U.S. Government Printing Office, February 1991).

core samples;[10] concentrations are already 25 percent above average interglacial levels and 75 percent above the level during the last glacial maximum.[11] Likewise, the atmospheric concentration of methane is increasing more than 400 times faster than natural rates of variability y.[12]

Climate models attempt to explain and predict how climate varies. The best current models predict global average surface temperatures will increase 0.5 to 2 'C by 2030. However, these models have large uncertainties. They also provide widely varying estimates of the geographic distribution and *consequences* of change.[13] No existing model is complete.[14] Taken together,

10 Lorius, et al., op. cit.; J.M. Barnola, et al., "Vostok Ice Core Provides 160,000-Year Record of Atmospheric CO_2," *Nature* 329:408-414, 1987.

11 IPCC, *Scientific* Assessment *of Climate Change,* op. cit., footnote 6.

12 J, Chappellez et al., "Ice-Core Record of Atmospheric Methane Over the Past 160,000 Years," *Nature* 345: 127-131, 1990.

13 U.S. Environmental Protection Agency, The Potential Effects of Global Climate Change on the United States, December 1989.

14 See Peter H. Stone, "Forecast Cloudy: The Limits of Global Warming Models," *Technology Review,* February/March 1992, pp. 32-40; Bette Hileman, "Web of Interactions Makes it Difficult to Untangle Global Warming Data," *Chemical and Engineering News,* Apr. 27, 1992, pp. 7-19.

existing models provide a range of predictions regarding future climate. After reviewing numerous models, the IPCC has concluded that if present emission trends continue, global average temperatures could rise by roughly an additional 1.0 ‘C by the year 2030.

If the climate were to change drastically, the effects would not be felt uniformly. Regional changes are extremely hard to predict because of constantly changing atmospheric and oceanic circulation patterns. Greater warming is likely to occur in some areas; negligible change or cooling is expected in others. Some regions may experience more drought, others more precipitation and perhaps changes in the frequency and intensity of storms.[15]

The significance of climate change predictions is not clear. Although the evidence that human activity is largely responsible for a changing climate is not beyond dispute,[16] data collected over the past century justify concern over climate. Reasons for concern include hypotheses that climate change could:

1. rapidly shift climate zones, preventing the adaptive migration of animals and plants;
2. speed the extinction of many species;
3. diminish water quality (a result of algal blooms in warmer water) in many freshwater lakes and rivers;
4. raise sea level, effectively reducing the amount of beaches and coastal wetlands;
5. reduce agricultural yields, possibly increase others, but change the distribution of crops;
6. increase the ranges of agricultural pests;
7. increase the demand for electricity;
8. diminish air quality (increased emissions from electric plants, speed atmospheric chemical reactions that produce atmospheric O_3);
9. change morbidity patterns, decrease winter mortality, increase summer mortality;
10. change infrastructure needs of many cities;
11. diminish freshwater resources in many regions.[17]

Since mitigating human impact on the environment is expensive and risky, economic uncertainty is often used to justify the expense of developing new remote sensing systems. The benefits derived from increased knowledge of the effects of global change could far outweigh the average yearly costs for space-based global change research (about $1 billion annually).

CURRENT ENVIRONMENTAL AND CLIMATE RESEARCH EFFORTS

Increased data on climate change and heightened international concern convinced the U.S. government of the need to address global change. In 1989, the Director of the Office of Science and Technology Policy, D. Allan Bromley, established an inter-agency U.S. Global Change Research Program (USGCRP) under the Committee on Earth and Environmental Sciences (in OSTP).[18] Established as a Presidential initiative in the FY 1990 budget, the goal of the program is to develop sound national and international policies related to global environmental issues. The USGCRP has seven main science elements:

1. climate and hydrodynamic systems,
2. biogeochemical dynamics,
3. ecological systems and dynamics,
4. earth systems history,
5. human interaction,
6. solid earth processes, and
7. solar influences.

Participation in the USGCRP involves nine government agencies and other organizations. 19 This research effort, and the efforts initiated by independent organizations (above), seek a better understanding of global

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15 Much of the information in this section originally appeared in U. S. Congress, Office of Technology Assessment, *Changing by Degrees.' Steps to Reduce Greenhouse Gases,* OTA-O-482 (Washington, DC: U.S. Government Printing Office, February 1991).

16 See Richard S. Lindzen, ‘‘Global Warming, The Origin and Nature of the Alleged Scientific Consensus, " *Regulation, The Cato Review of Business and Government,* Spring 1992. Lindzen states, “Not only are there major reasons to believe that models are exaggerating the response to increasing carbon dioxide, but, perhaps even more significantly, the models' predictions for the past century incorrectly describe the pattern or warming and greatly overestimate its magnitude. ’

17 U.S. Environmental protection Agency, The potential Effects of Global Climate Change on the United States, EPA-230-05-89-050, December 1989.

18 For further information see “Our Changing Planet: The FY 1992 Research Plan,'' The U.S. Global Change Research Program, A Report by the Committee on Earth and Environmental Sciences, a supplement to the U.S. President's Fiscal Year 1992 Budget.

19 Including the Smithsonian Institution and the Tennesee Valley Authority.

change. All will rely on remote observations of atmosphere, oceans, and land for data.

Mission to Planet Earth

The concept of Mission to Planet Earth evolved over several years.[20] In 1982, at a U.N. space conference (Unispace '82), NASA proposed a comprehensive, U.S.-led program to monitor the health of the Earth. Called the Global Habitability Program, it was largely ignored by the conference participants.[21] In 1985, the Global Habitability concept was transformed, NASA sought to apply the concepts described by global habitability to research focused on long-term physical, chemical, and biological changes on a global scale.[22] The research effort will rely on data collected by ground, air, and space-based systems. NASA has coordinated its efforts with the Committee on Earth and Environmental Sciences, and agencies of the Federal Government.

NASA's stated goal for Mission to Planet Earth is to ''establish the scientific basis for national and international policymaking relating to natural and human induced changes in the global Earth system."[23] The primary program objectives include establishing an integrated, comprehensive, and sustained program to document the Earth system on a global scale. Mission to Planet Earth scientists will conduct focused, exploratory studies to improve understanding of the physical, chemical, biological and social processes that influence Earth system changes and trends on globaI and regional scales. NASA-supported scientists will provide information for policymakers based on integrated conceptual and predictive Earth system models.

Mission to Planet Earth will address the following key uncertainties regarding climate change:

1. role of greenhouse gases,
2. role of clouds,
3. role of oceans,
4. role of polar ice sheets,
5. land surface hydrology, and
6. ecosystems response.

These parallel the priorities set by the Committee on Earth and Environmental Sciences. NASA has worked to align the instruments proposed for EOS with the scientific and policy goals addressed by the U.S. Global Change Research Program.

EOS AND RELATED SYSTEMS

NASA considers the Earth Observing System the cornerstone of the Mission to Planet Earth. EOS is to be a multiphase program that NASA expects to last about two decades.[24] The core of EOS will be three copies of two satellites, capable of being launched by an Atlas II-AS booster, a medium lift launcher that is under development.

The EOS program begins with a number of 'phase one' satellites (most of which predate the EOS concept, and are funded through other programs) that would provide observations of specific phenomena. The Upper Atmosphere Research Satellite (UARS), which has already provided measurements of high levels of chlorine monoxide (C10)[25] above North America, is an example of an EOS phase one instrument. NASA's EOS plans also include three smaller satellites (Chemistry, Altimeter and Aero), that would observe specific aspects of atmospheric chemis-

m For more background on the genesis of Mission 10 Planet Earth, see Burton Edelson, Science, Jan. 25, 1985, (Editorial); CRS Report to Congress, "Mission to Planet Earth and the U.S. Global Change Research program," Marcia S. Smith and John Justis, June 19, 1990; Sally K. Ride, ' 'Leadership and America's future in Space, " A Report to the NASA Administrator, August 1987. The "Ride Report, " as this document has become known, strongly advocates Mission to Planet Earth as a top priority for NASA's future.

21 See U.S. Congress, Office of Technology Assessment, *UNISPACE '82: A Context for International Cooperation and Competition, OTA-ISC-TM-26* (Washington DC: U.S. Government Printing Office, March 1983), for more information regarding U.S. proposals and the debate over militarization.

22 Ibid.

23 presentation of Shelby Tilford, Director, NASA Earth Science and Applications Division, to the Woods Hole Space Science and Applications Advisory Committee Planning Workshop, July 1991.

24 See ch. 2, ch. 5, and app. B for more details about NASA'S Mission to Planet Earth and EOS.

25 Chlorine monoxide is a chemical compound that, when affected by sunlight in the upper atmosphere, leads to degradation Of O_3. Ozone is formed m the stratosphere by the reaction of atomic oxygen (0) with molecular oxygen (02). This process is begun by the dissociation of O_2 into O by absorption of solar ultraviolet radiation at wavelengths below 240 nm. This process occurs at altitudes above 25 km. This process can be interrupted by Cl: $Cl+O_3 \rightarrow ClO+O_2$ . . . $ClO+O \rightarrow Cl+O_2$. C1O is therefore a precursor of disappearing ozone.

Box A-3-Measurements of Ozone Depletion

For most global change and climate change research, a combination of satellite and in situ measurements is required to obtain sufficient data. One of the best examples of the need for both types of measurements is the discovery of the ozone hole above Antarctica. Researchers from the United States and Great Britain had been measuring atmospheric conditions over Antarctica: the U.S. team relying on satellite sensors; the British team using ground-based spectrophotometers. In 1983-84, the British team recorded a series of measurements of ozone that seemed extraordinarily low (below 200 Dobson units).[1] Data from the Total Ozone Mapping Spectrometer (TOMS) aboard Nimbus-7 and the Solar Backscatter Ultraviolet Radiometer (SBUV) aboard polar-orbiting NOAA satellites were automatically processed by computer before being analyzed. U.S. scientists felt that any readings below 200 Dobson units would be outside the range of possibility and were likely the result of a sensor anomaly; hence they designed a computer algorithm that ignored such measurements. Data were stored, and subsequently reviewed, but these readings were originally dismissed.

Neither did the British team believe its own readings. The first conclusion that project director Joe Farman and his team reached was that their ground-based sensors, which were old, had been improperly calibrated. Yet when anew, updated sensor produced similar results, they realized that the loss of ozone was much greater than anyone expected. This experience demonstrates one of the advantages of ground-based sensors: sensor packages can be easily replaced to validate the performance of the original system. It also demonstrates the dangers of establishing a threshold for expected results.

Researchers have learned several lessons from the discovery of cyclical ozone depletion over Antarctica. First, because ground-based sensors observe specific phenomena from a site whose environmental parameters can be thoroughly characterized, they are sometimes more adept at detecting regional change or unusual local environmental conditions than are satellite-based sensors. Second, although it is sometimes difficult to distinguish between real results (signal) and invalid measurements (noise), setting predetermined limits on natural phenomena while studying global change is not judicious. Third, even accepted models, such as the one that provided the parameters for the U.S. research team, can be far wrong. All models should be scrutinized and tested periodically.

1 The Dobson unit is a measurement of thickness standardized to the thickness of the ozone layer at 32 degrees Fahrenheit and sea level atmospheric pressure. One Dobson unit is equivalent to .001 cm of ozone.

SOURCE: Office of Technology Assessment, 1993.

try, ocean topography, and tropospheric winds. In addition, NASA plans to include data from "Earth Probes,' additional copies of sensors that monitor ozone and ocean productivity, in the EOS Data and Information System. See box A-3 for a description of ozone measurement.

The EOS Data and Information System (EOSDIS) will be a key feature of EOS (box A-4). According to NASA, data from the EOS satellites will be available to a wide network of users at minimal cost through the EOSDIS. NASA will develop EOSDIS so it can store data and distribute them to many users simultaneously. EOSDIS will require significant technology development, especially in software, storage, and data processing, EOSDIS will require a continued funding effort that will reach $254 million in 1996. In total, EOSDIS is expected to cost $946 million between 1991 and 1997, A future OTA report will examine the data issues related to remote sensing.

NASA plans to operate various EOS sensors for 15 years, providing researchers with data covering a complete solarcycle[26] and several El Ninos,[27] two large natural variables affecting Earth's climate. EOS sensors will be grouped or co-located by function to

26 Approximately every 11 to 15 years, the Sun completes one solar cycle.

27 A slight warming of the upper waters of the southern Pacific, occurring about every 4 to 7 years.

Box A-4-The EOS Data and Information System

A central element of NASA's Mission to Planet Earth is the EOS Data and Information System. This system is intended to process, store, and distribute the data obtained from Mission to Planet Earth flight projects and scientific investigations. EOSDIS is intended to be sufficiently flexible to incorporate previously archived data, measurements from non-EOS spacecraft, and ground-, ocean-, and space-based measurements conducted by other Federal, foreign, and international agencies. Through the EOSDIS program, NASA has promised to provide a comprehensive system t hat will merge data from a wide variety of sources to serve integrated, interdisciplinary research. EOSDIS **is ambitious and complex; it must manage vast streams of data perhaps as many as 400 trillion bytes per year.** This is roughly equivalent to the amount of data that would fill 4 million 100-megabyte hard drives (approximately the amount of storage purchased with a new personal computer). NASA has made comparisons between the amount of data EOSDIS will handle and the amount of information stored in t he Library of Congress. These comparisons are faulty, since the Library of Congress contains paintings, movies, pictures, in addition to printed media. It is more rational to think of the amount of data to be handled in EOSDIS in terms of the largest data bases currently on line, and no system in use to date has come close to handling this amount of data.

EOSDIS must also make these data easily usable for a very wide variety of users, possibly numbering as many as 100,000 people, many of whom will have little detailed technical knowledge of remote sensing. EOSDIS is intended to provide the tools needed to transform data into information, through activities such as the development and integration of algorithms ("formulas") for data analysis, the communication and exchange of data among scientists, the maintenance of standards and formats for data and information, and the archiving of scientific information for access by others.

Structurally, EOSDIS will consist of at least seven research science-oriented Distributed Active Archive Centers (DAACS), and several Affiliated Data Centers. The seven sites selected as EOS DAACS are currently functioning as relatively independent data centers. When linked together and integrated into EOSDIS, the DAACS will receive raw data from EOS spacecraft and other sources, process the data, and provide data and information to users. Three systems will operate at each DAAC:

1. a product generation system (PGS),
2. a data archive and distribution system (DADS), and
3. an information management system (IMS).

The product generation system at each DAAC will convert raw data signals into standard sets of Earth science data, using data processing software developed by t he scientific user community. The data archive and distribution system at each DAAC will serve as the archive and distribution mechanism for EOS data products, as well as other data sources both within and outside the EOS program. The information management system at each DAAC will give users access to all data throughout EOSDIS, as well as help in locating and ordering data. When fully operational, a scientist signing onto EOSDIS at any DAAC site will have complete access to all data sets anywhere in EOSDIS, regardless of physical location. NASA has promised to have processed data available to scientists through EOSDIS within **4** days of initial observations.

NASA has adopted an "evolutionary" approach for the development of EOSDIS, since pre-definition of all EOSDIS requirements is impossible (e.g., the science and data requirements for studies of the Earth system will change as our knowledge and experience grow, and most EOSDIS users are currently not practicing Earth system scientists; some are not yet born). EOSDIS is to have an "open" architecture, meaning that new hardware and software technologies will be easily inserted as EOSDIS evolves, and changing user requirements can be accommodated. Feedback from users is intended to inform each new increment of EOSDIS, a "learn-as-you-go" approach.

(continued on next page)

Box A-4-The EOS Data and Information System-Continued

NASA is currently developing an early EOSDIS system ("Version O") to improve access to existing data and to test the interoperability of existing systems. Version O includes the development of user-friendly "pathfinder" data sets from archived data of NOAA, DOD, and Landsat satellites, developing commonality among DAAC data systems, and protot yping a few EOSDIS technologies. Version O is scheduled to be in place by late 1994. Versions 1 through 6 are planned to be delivered through a single contractor, Hughes Information Technology. Version 1 will provide PGS, DADS, and IMS functions at each DAAC, and examine prototyping technologies for data processing and scheduling functions for EOS instruments. NASA plans to have Version 1 operational at all DAACS by 1996. Version 2 will be the first full-scale operational EOSDIS, using data from the first EOS platform, and is scheduled to be operating by the mid-1998 launch of the EOS AM1 spacecraft. Versions 3 through 6 will follow as subsequent spacecraft are launched and science needs evolve.

SOURCE: National Aeronautics and Space Administration, General Accounting Office, National Research Council, House of Representatives Science, Space and Technology Committee

provide simultaneous coverage by complementary instruments. Another advantage to the broad array of sensors carried by the EOS platforms will be the ability to isolate the effects of individual variables. A goal of EOS is to make possible real-time analysis of these observations.

NASA has scheduled the launch of the first EOS satellite for 1998. Critics of EOS claim that this schedule does not allow for timely data gathering. The possibility exists that gaps in monitoring stratospheric ozone could occur in 1995-2000, especially if the Upper Atmosphere Research Satellite (UARS, the first of the EOS Phase One satellites) that concentrates on measuring upper atmosphere ozone, fails to live past its expected lifetime (1995). Germany had been planning a satellite to monitor ozone, but tight budgets may prevent such an effort. TOMS (total ozone mapping spectrometers) will be available on other satellites, but may not have the ability to "record in detail the chemical changes occurring in the stratosphere."[28] Scientists express concern that similar gaps will exist in other climate monitoring efforts, and will likely arise during the lifetime of EOS. The reality of austere budgets will affect global change research: smaller than expected budgets will not allow funding for all observation/monitoring projects, despite needs for scientific information.

EOS INSTRUMENTS

EOS **Phase** One-EOS Phase One is a series of small satellites that have been grouped together under the aegis of EOS. Most of these satellites were funded under existing programs prior to inclusion in the EOS program. Phase one includes the instruments below,[29] which will be launched beginning in 1993.

- Sea Wide Field Sensor (SeaWiFS), an ocean color sensor to study ocean productivity and ocean/atmosphere interaction, still an area of climate uncertainty.
- Total Ozone Mapping Spectrometer, additional copies of the TOMS instruments to fly on NASA explorer class satellites and on Japan's Advanced Earth Observation Satellite (ADEOS). An earlier version of TOMS had flown on Nimbus-7 in 1978, and on a (then) Soviet Meteor-3 on August 15, 1991. Japan has developed the ADEOS as an international effort (app. D); the U.S. is providing two of the sensors,[30] France is Providing one,[31] and Japan will develop several others, including an interferometric monitor for greenhouse gases and

[28] "Gaps Loom in Satellite Data," *Nature, vol.* 335, p. 662, Feb. 20,1992.

[29] The number of Phase One experiments that will survive the most recent budget cut was unknown at the time this report went to press. NASA will also include data from POES, GOES, DMSP, Landsat and other satellites in the EOSDIS, hence NASA also lists data from these satellites as phase one data.

[30] The sensors are the total ozone mapping spectrometer (TOMS) and NASA Scatterometer.

[31] Polarization and Directionality of the Earth's Reflectance (POLDER).

an improved limb atmospheric spectrometer. ADEOS will be used to measure ozone and other gases, as well as measure ocean surface winds.

- The NASA Scatterometer, an instrument designed to study the ocean's surface to determine wind patterns and air-sea interaction, now tentatively scheduled for flight on ADEOS-11.
- The Tropical Rainfall Measurement Mission (TRMM), also a joint program with Japan, will make extensive measurements of precipitation, clouds and hydrology in tropical regions, which cannot be time-sampled adequately from polar orbit.[32]
- TOPEX/Poseidon, a group of sensors for measuring ocean topography and altimetry on a platform launched by France on an Ariane booster in August 1992.

The Upper Atmosphere Research Satellite, launched in September 1991, became the first of these Phase One satellites to enter service. Although its development began in 1985, UARS is viewed as the first major project of the Mission to Planet Earth. The UARS platform carries 10 instruments in order to meet two project goals:

1. Observe the atmosphere over the northern hemisphere during two winters. The northern hemisphere has a greater terrain/ocean ratio, thus providing a highly dynamic interaction between earth, ocean and atmosphere, Although UARS may function for over nine years, the instrument for these observations (the Cryogenic Limb Array Etalon Spectrometer or CLAES) requires cryogens that will be exhausted in about 2 years.
2. Observe dynamic processes (presence of chlorofluorocarbons, stratospheric winds, etc.) responsible for the hole in the ozone layer above Antarctica.[33]

Other instruments carried on the UARS include an improved Stratospheric and Mesospheric Sounder used to observe infrared molecular emissions, a microwave limb sounder used to measure chemicals (especially chlorine monoxide) in the upper atmosphere, a halogen occultation experiment, a wind imaging interferometer, a solar ultraviolet spectral irradiance monitor, a solar stellar irradiance instrument, and a particle environment monitor.[34]

EOS-AM

The EOS-AM satellites,[35] the first of which NASA plans to launch in June 1998, will characterize the terrestrial surface and examine the aerosol and radiation balance within clouds. It will carry five sensors.

1. The Clouds and Earth's Radiant Energy System (CERES) will provide earth scientists with measurements of cloud and radiation flux. The measurements will be taken with two broadband scanning radiometers, each functioning on three charnels. These radiometers will calculate the amount of radiation that is reflected by the Earth's surface and the amount reflected by clouds. Comparing these measurements will allow a better understanding of the role that clouds play in regulating the earth's climate. Measurements of reflected radiation and the reflective efficiency of different cloud types will enable development of global oceanic and atmospheric models.
2. The Moderate Resolution Imaging Spectroradiometer—(MODIS), will be used to measure biological and physical processes that do not require along-track pointing. These applications will include long-term observation of surface processes/global dynamics such as: surface temperature; ocean color; chlorophyll fluorescence; concentration of chlorophyll; vegetation cover, productivity; fires; snow cover/reflectance; cloud cover; cloud properties. Data collected by MODIS will be used to take global measurements of chlorophyll, dissolved organic matter and other constituents that provide insight about ocean productivity. MODIS will provide data useful to the determination of the role of the oceans in the

32 Shelby G. Tilford, Gregory S. Wilson and Peter W. Backlund, "Mission To Planet Earth," paper presented at the 42d Cong. of the International Astronautical Federation Oct. 5-11, 1991, Montreal, Canada.

33 "Discovery t. Launch First Element of NASA's Mission t. Planet Earth," *Aviation Week and Space Technology*, Sept. 9, 1991, pp. 63-67.

34 Ibid.

35 For a more complete description of EOS instruments, see NASA's 1993 EOS Reference Handbook, NASA, Earth Science Support Office.

global carbon cycle. These data will have applications in models as well as providing information regarding the productivity of aquatic and terrestrial plants. Measurements of total precipitation and aerosol properties will also be facilitated by MODIS measurements.

3. The Multiangle Imaging Spectra-Radiometer (MISR) will be the only EOS instrument that will provide information on cloud and surface angular reflectance. The instrument is designed to obtain images of each scene from multiple angles and in four spectral bands. The data are collected using nine charged-coupled device (CCD) pushbroom cameras. Measurements taken by MISR will allow researchers to determine the effects of aerosols in the atmosphere, understand how different cloud types affect the radiation budget, evaluate some changes in the Earth's forest and deserts, and study aspects of interaction between biophysical and atmospheric processes.
4. The Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) is an imaging radiometer that will be used to provide high spatial resolution images of land, water, and clouds. ASTER is one of Japan's contributions to the EOS program. Images taken in the visible and near infrared, shortwave infrared, and thermal infrared wavelengths will be used in the study of soil and rock formations, to monitor volcanoes, and to measure surface temperatures, emissivity and reflectivity. The visible and near infrared and shortwave infrared channels will also have the ability to provide information on land use patterns and vegetation. The very near infrared and thermal infrared capabilities will provide information on coral reefs and glaciers. Some evaporation and land and ocean temperature readings will be possible as well.
5. Measurements of Pollution In The Troposphere, or MOPITT, a correlation spectrometer, will provide measurements of pollution in the troposphere at three wavelengths in the near infrared. It will specifically measure levels of carbon monoxide and methane.

NASA plans to include the Earth Observing Scanning Polarimeter (EOSP) on the second AM platform (an earlier flight of EOSP was rejected by NASA—see app. B). EOSP will be designed to map the radiance and linear polarization of reflected and scattered sunlight through 12 spectral bands, and provide global measurements of aerosol distribution and cloud properties. EOSP is a polarimeter that scans cross-track, providing a global profile of aerosol optical thickness. These data will correct clear-sky ocean and land measurements that are of critical importance to other optical measurements of the Earth's surface.

In addition to EOSP, AM-1 will carry a second instrument not on the first AM platform. The Tropospheric Emission Spectrometer (TES) will be an infrared imaging spectrometer that will provide global three-dimensional profiles of all infrared-active species from surface to lower stratosphere. This information will be used to study greenhouse gases, tropospheric ozone, precursors of acid rain, and gas exchange in the stratosphere leading to ozone depletion.

EOS COLOR

EOS-Color (1998) will measure oceanic biomass and productivity.

- **The** Sea Wide Field of view Sensor (SeaWiFS-11) will be a multi-band (8) imager that will operate in the very near infrared portion of the spectrum. SeaWiFS will be used to observe chlorophyll, dissolved organic matter and pigment concentrations in the ocean. The sensor will contribute to understanding the health of the ocean and concentration of life forms in the ocean.

EOS AERO

EOS-Aero (2000) will measure atmospheric aer-0s01s.

- **The** Stratospheric Aerosol and Gas Experiment (SAGE III) will be a grating spectrometer, designed to obtain global profiles of aerosols, ozone, water vapor, nitrous oxides, airborne chlorine, clouds temperature and mesospheric, stratospheric and tropospheric pressure. SAGE is a follow-on to earlier instruments of the same name. SAGE III will be self-calibrating, and will have a better vertical range than its predecessors.

EOS-PM

EOS-PM (2000) will examine clouds, precipitation and the Earth's radiative balance; will meas-

ure terrestrial snow a nd sea ice; observe sea surface temperature and monitor ocean productivity.

- **CERES** (see above).
- MODIS-N (see above).
- The Atmospheric Infrared sounder (AIRS) is a high spectral resolution sounder that will provide temperature and humidity profiles through clouds. It will measure outgoing radiation and be able to determine land skin surface temperature. In addition, the sounder will be capable of determining cloud top height and effective cloud amount, as well as perform some ozone monitoring.
- The Advanced Microwave Sounding Unit (AMSU-A) and the Microwave Humidity Sounder (MHS) are both microwave radiometers that will provide all weather atmospheric temperature measurements from the surface up to 40 km (AMSU) and atmospheric water vapor profiles (MHS).
- The Multifrequency Imaging Microwave Radiometer (MIMR) will provide passive measurements of precipitation, soil moisture, global snow and ice cover, sea surface temperature, cloud water, water vapor and wind speed, MIMR will be provided to NASA by the European Space Agency.

EOS-ALT

EOS-Alt (2002) will observe ocean circulation and ice sheet mass balance using the following instruments:

- The EOS altimeter (ALT) will be a dual frequency radar altimeter. ALT will provide mapping data for sea surface and polar ice sheets. The return pulse of the radar can also provide information on ocean wave height and wind speed.
- The Geoscience Laser ranging system and altimeter (GLRS-A) will be tailored to measure geodynamic, ice sheet, cloud, and geological processes and features.

EOS-Chem

EOS-Chem (2002) will track atmospheric chemical species and their transformations; and measure ocean surface stress.

- The High Resolution Dynamics Limb Sounder (HIRDLS) will be an infrared seaming radiometer that derives from similar units deployed on the Nimbus and UARS satellites, It will be used to sound the upper troposphere, stratosphere and mesosphere to determine temperature; concentrations of O_3, greenhouse **gases,** and aerosols; locations of polar stratospheric clouds/cloud tops.
- The Active Cavity Radiometer Irradiance Monitor (ACRIM) is designed to measure solar output and variations in the amount of radiation that enters the atmosphere.
- The Stratospheric Aerosol and Gas Experiment (SAGE III) will be the third in a series of similar instruments. See description under AERO, above.
- Microwave Limb Sounder (MLS) is a passive, limb sounding radiometer, The MLS will be designed to study and monitor atmospheric processes that affect ozone. Particular emphasis will be given to the impact of chlorine and nitrogen.
- NASA may try to fly the GPS Geoscience Instrument (GGI) aboard the Chem satellite. GGI will be designed to contribute to the accuracy of mapping data collected by other sensors (down to the centimeter level). It will also play a role in ionospheric gravity wave detection.

The primary EOS spacecraft, AM and PM, will be replaced over time to ensure at least 15 years of coverage, Follow-on payloads will remain flexible to meet needs as determined by the evolution of scientific understanding derived from earlier launches.[36]

[36] Statement by L.A. Fisk, Associate Administrator for Space Science and Applications, National Aeronautics and Space Administration, before the Subcommittee on Science, Technology and Space, Committee on Commerce, Science and Transportation, United States Senate (102d Cong.), Feb. 26; 1992.