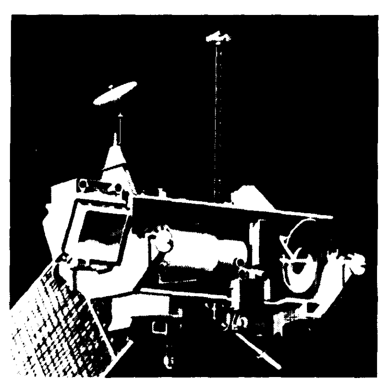
Global Change Research 5

Global change encompasses many coupled ocean, land, and atmospheric processes. Scientists currently have only a modest understanding of how the individual elements that affect climate, such as clouds, oceans, greenhouse gases, and ice sheets, interact with each other. Additionally, they have only limited knowledge about how ecological systems might change as the result of human activities (plate 7) and natural Earth processes. Because changes in climate and ecological systems may pose a severe threat to mankind, but the uncertainties in both are extremely large, the study of global change has assumed major importance to the world. Consequently, scientists and concerned policymakers have urged development of an integrated program of Earth observations from space, in the atmosphere, and from the surface.



THE U.S. GLOBAL CHANGE RESEARCH PROGRAM

The U.S. Government has developed a comprehensive research program to gather data on global change and evaluate its effects (box 5-A). The diverse elements of the U.S. Global Change Research program (USGCRP) are coordinated by the Committee on Earth and Environmental Sciences (CEES), a committee of the Federal Coordinating Council for Science, Engineering Sciences, and Technology (FCCSET), within the Office of Science and Technology Policy.

The U.S. effort to study global change responds in part to an international framework of research and policy concerns articu-

[1] Uncertainties in possible adaptation strategies are also extremely large. See the forthcoming report of an assessment of systems at risk from global change, Office of Technology Assessment.

Box 5-A—U.S. Global Change Research Program

Global environmental and climate change issues have generated substantial international research activity. Increased data on climate change and heightened international concern convinced the U.S. Government of the need to address global change in a systematic way. 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.[1] Established as a Presidential Initiative in the FY 1990 budget, the goal of the program is to provide the scientific basis for the development of sound national and international policies related to global environmental problems. The USGCRP has seven main science elements:

- climate and hydrodynamic systems,
- biogeochemical dynamics,
- ecological systems and dynamics,
- earth systems history,
- human interaction,
- solid earth processes, and
- solar influences.

Participation in the USGCRP involves nine government agencies and other organizations.[2] Research efforts coordinated through the USGCRP seek a better understanding of global change and the effects of a changing environment on our daily lives. Most research projects rely on remote observations of atmosphere, oceans, and land for data. Coordination of research across agencies should eliminate duplication and increase cooperation, and at minimum will promote communication between agencies. The Committee on Earth and Environmental Sciences (CEES) makes suggestions to federal agencies, and federal agencies can raise items for consideration through the CEES. Although this process can be cumbersome, most researchers acknowledge that the program has brought a degree of coordination never before seen in federally sponsored research of this type. However, the attempts at coordination do not assure a comprehensive program that tackles the most important issues. In addition, now that the USGCRP is underway, it is no longer treated as a Presidential Initiative. This change of status has led to concerns that funds previously "fenced off" for global change research will not be forthcoming.[3]

1 For further information see Committee on Earth and Environmental Sciences, *Our Changing Planet: The FY 1993 U.S. Global Change Research Program* (Washington, DC: National Science Foundation, 1993).

2 Including the Smithsonian Institution and the Tennessee Valley Authority.

3 These issues are addressed in a forthcoming OTA background paper, *EOS and the USGCRP*.

SOURCE: Office of Technology Assessment, 1993.

lated in reports of the Intergovernmental Panel on Climate Change (IPCC), the International Geosphere-Biosphere Programme, and the World Climate Research Programme (WCRP) and supported by numerous national scientific panels. The USGCRP is attempting to "produce a predictive understanding of the Earth system to support . . . national and international policymaking activities that cover a broad spectrum of global and regional environmental issues,' by:

- documenting global change,
- enhancing understanding of key processes, and
- predicting global and regional environmental change.

[2] Committee on Earth and Environmental Sciences, *Our Changing Planet: The FY 1993 U.S. Global Change Research Program* (Washington DC: National Science Foundation, 1993), pp. 3-4.

NASA'S MISSION TO PLANET EARTH

NASA established its Mission to Planet Earth (MTPE) in the late 1980s as part of its program in Earth sciences, MTPE includes the Earth Observing System (EOS), which consists of a series of satellites capable of making comprehensive Earth observations from space (figure 5-1);3 Earth Probe satellites for shorter, focused studies (box 5-B); and a complex data archiving and distribution system called the Earth Observing System Data and Information System (EOSDIS). Until NASA launches the first EOS satellite, MTPE research scientists will rely on data gathered by other Earth science satellites, such as UARS, the U.S.-French TOPEX/Poseidon,[4] Landsat, and NOAA's environmental satellites. Data from the EOS sensors may provide information that will reduce many of the scientific uncertainties cited by the IPCC--climate and hydrologic systems, biogeochemical dynamics, and ecological systems and dynamics.[5] NASA has designed EOS to provide calibrated data sets[6] of environmental processes occurring in the oceans, the atmosphere, and over land.

EOS science priorities (table 5- 1) are based primarily on recommendations from the Intergovernmental Panel on Climate Change and CEES of the FCCSET. NASA has designed EOS to **return data over at least 15 years of operation; its scientific value will be compromised if measurements begun in the late 1990s do not continue well into the next century. This raises a critical issue for Congress: whether a commitment to an Earth Observing System, which may require outlays on the order of $1 billion/year in current dollars through about 2015, is sustainable.** Maintaining this level of investment will require Congress' continued interest in measuring climate and environmental parameters and assessing the causes of global environmental change in the face of other demands on the Federal budget. It will also require continuing, clear support from several presidential administrations.

NASA'S early plan for EOS was extremely ambitious, technically risky, and costly. In 1991, Congress told NASA that it should plan for reduced future funding for the first phase of EOS (fiscal year 1992 through fiscal year 2000), and to cut its funding expectations from a projected $17 billion to $11 billion.[7] This reduction led to a major restructuring of the EOS program.[8] In the restructuring, NASA retained instruments that focus on climate issues and reduced or eliminated those that would have emphasized gathering data on ecology and observations of Earth's surface. **The restructured program's first priority is acquiring data on global climate change.** As a result, NASA has de-emphasized missions designed to improve scientific understanding of the middle and upper atmosphere and of solid Earth geophysics. The development of remote sensing technology has also been affected by these shifts as NASA has de-emphasized advanced sensors for very high-resolution infrared, far-infrared, and sub-millimeter wave spectroscopy. NASA also

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[3] See app. A for a summary of the MTPE instruments and satellites.

[4] This U.S./French cooperative satellite was successfully launched into orbit Aug. 10, 1992 aboard an Ariane 4 rocket.

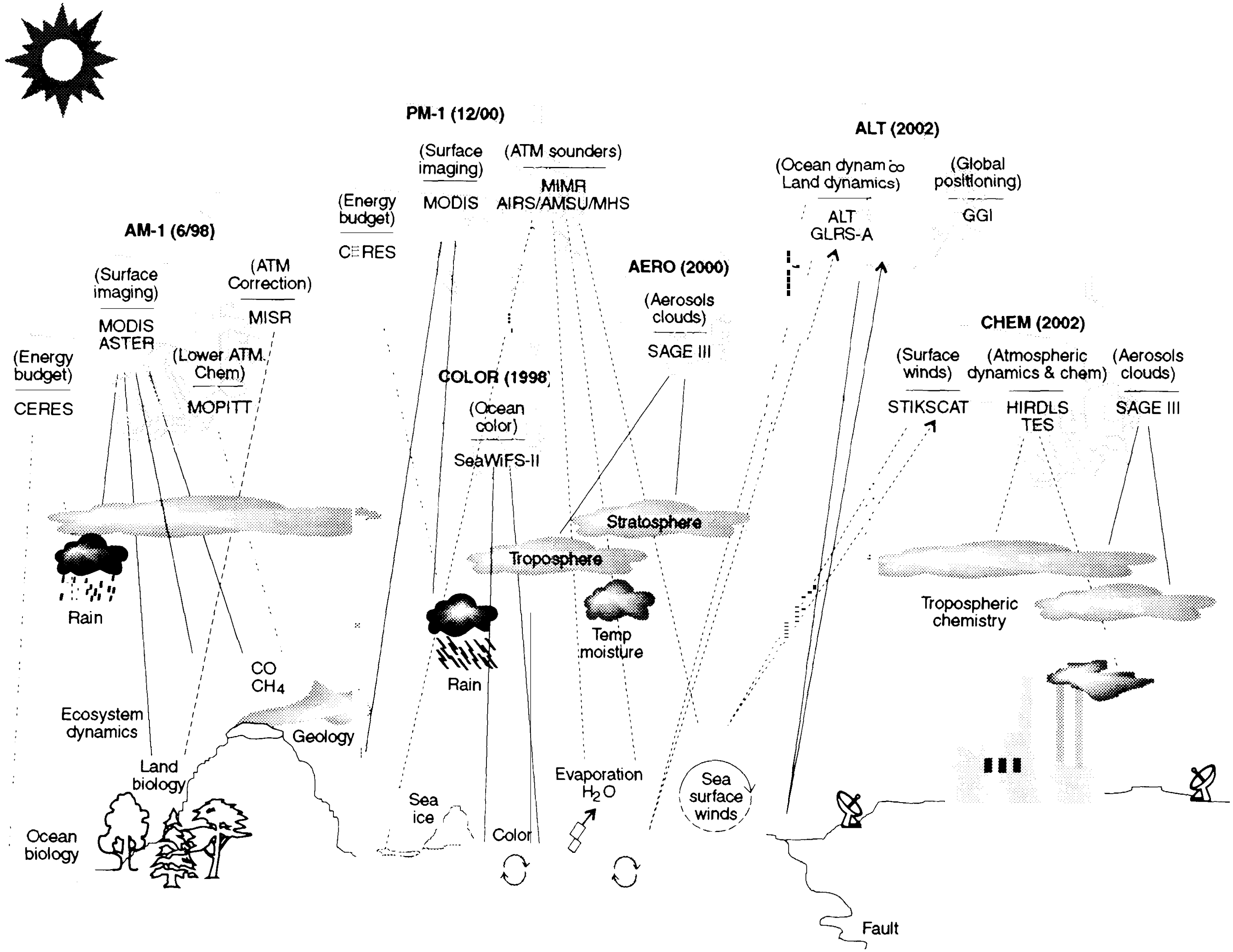
[5] ''Our Changing Planet: the FY 1991 Research Plan,'' The U.S. Global Change Research Program, a report by the Committee on Earth and Environmental Sciences, October 1990.

[6] NASA has proposed to build and launch two sets of three satellites. The first set (called the AM satellite because it will follow a polar orbit and cross the equator every morning) would be launched in 1998, 2003, and 2008. The second set (called the PM satellite) would be launched in 2000, 2005, and 2010.

[7] U.S. Senate, Committee on Appropriations, ''Departments of Veterans Affairs and Housing and Urban Development, and Independent Agencies Appropriation Bill, 1993, " report to accompany H.R. 2519, 102-107, July 2, 1992, pp. 52-53.

[8] A number of scientists urged NASA to restructure the program on grounds of technical and programmatic risk. See, for example, *'Report of the Earth Observing System (EOS) Engineering Review Committee, ' September 1991; Berrien Moore III, "Payload Advisory Panel Recommendations," NASA manuscript, Oct. 21-24, 1991.

Figure 5-' —NASA's Planned Earth Observing System Satellites and Sensors



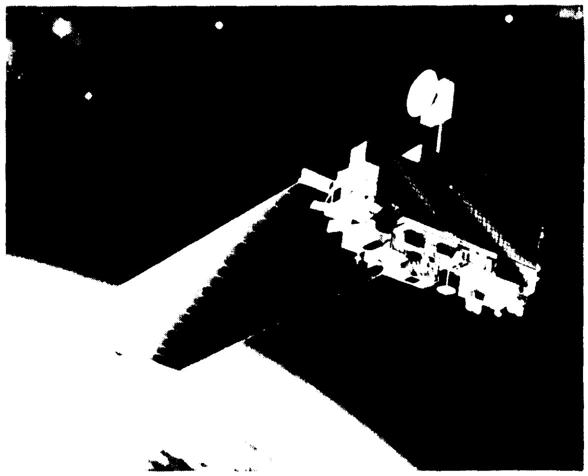
The figure depicts the primary function of major instruments on board six of the EOS satellites. These sensors will measure various Earth and atmospheric processes. Most sensors are passive, with two active sensors distinguished by arrowheads.

SOURCE: National Aeronautics and Space Administration, 1992.

Box 5-B–NASA's Earth Observing System (EOS)

EOS is the **centerpiece** of NASA's contribution to the Global Change Research Program. Managed by NASA's newly created Mission to Planet Earth Office,[1] EOS is to be a multiphase program lasting about two decades. The original EOS plan called for NASA to build a total of six large polar-orbiting satellites, which would fly two at a time on 5-year intervals over a 15-year period. In 1991, funding constraints and concerns over technical and budgetary risk[2] narrowed its scope.

Figure 5-2—Artist's Conception of NASA's Earth Observing System AM-1 Platform, Scheduled 1998 Launch.



SOURCE: Martin Marietta Astro Space.

The core of the restructured EOS consists of three copies each of two satellites (smaller than those originally proposed, and capable of being launched by an Atlas II-AS booster), designed to observe and measure events and chemical concentrations associated with environmental and climate change. NASA plans to place these satellites, known as the EOS-AM satellite (which will cross the equator in the morning while on its ascending, or northward, path) and EOS-PM satellite (an afternoon equatorial crossing) in polar orbits. The three AM satellites will carry an array of sensors designed to study clouds, aerosols, Earth's energy balance, and surface processes (figure 5-2). The PM satellites will take measurements of clouds, precipitation, energy balance, snow, and sea ice.

NASA plans to launch several "phase one" satellites in the early and mid 1990s that will provide observations of specific phenomena. Most of these satellites pre-date the EOS program and are funded separately. The Upper Atmosphere Research Satellite (UARS), which has already provided measurements of high levels of ozone-destroying chlorine oxide 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 will observe specific aspects of atmospheric chemistry, ocean topography, and tropospheric winds. In addition, **NASA plans to include data from "Earth Probes," and from additional copies of** sensors that monitor ozone and ocean productivity, in the EOS Data and Information System (EOSDIS).

NASA will develop EOSDIS[3] so it can store and distribute data to many users simultaneously. This is a key feature of the EOS program. According to NASA, data from the EOS satellites will be available to a wide network of users at minimal cost to researchers through the EOSDIS. NASA plans to make EOSDIS a user-friendly, high-capacity, flexible data system that will provide multiple users with timely data as well as facilitate the data archiving process critical to global change research. EOSDIS willl require substantial amounts of memory and processing, as well as extremely fast communications capabilities.

1 Created in March 1993 when the Office of Space Science and Applications was split into the Office of Mission to Planet Earth, the Office of Planetary Science and Astrophysics, and the Office of Life Sciences.

2 National Research Council Orange Book; "Report of the Earth observing System (EOS) Engineering Review Committee," September 1991.

3 Hughes information Technology won the contract to develop EOSDIS in 1992.

SOURCE: Office of Technology Assessment, 1993.

Table 5-1—EOS Science and Policy Priorities[a]

Water and energy cycles:
• Cloud formation, dissipation, and radiative properties, which influence the scale and character of the greenhouse effects.
• Large-scale hydrology and moist processes, including precipitation and evaporation.
Oceans:
• Exchange of energy and chemicals between ocean and atmosphere and between ocean surface layers and deep ocean.
Chemistry of troposphere and lower stratosphere:
• Links to hydrologic cycie and ecosystems, transformation of greenhouse gases in atmosphere, and interactions with climatic change.
Land surface hydrology and ecosystem processes:
• Improved estimates of runoff over surface and into oceans.
• Sources and sinks of greenhouse gases.
• Exchange of moisture and energy between land surface and atmosphere.
Glaciers and polar ice sheets:
• Predictions of sea level and global water balance.
Chemistry of middle and upper stratosphere:
• Chemical reactions, solar-atmosphere relations, and sources and sinks of radiatively important gases.
Solid Earth:
• Volcanoes and their role in climate change.

a List in approximate priority order; these priorities are based on a program that would spend approximately $8 billion between 1991 and 2000.

SOURCE: Berrien Moore III and Jeff Dozier, "Adapting the Earth Observing System to the Projected $8 Billion Budget: Recommendations from the EOS Investigators," Oct. 14, 1992, unpublished document available from authors or from the NASA Mission to Planet Earth Office.

reduced the size of the planned satellites and increased their number. The restructured program is now more resilient to the loss of a single satellite during launch or in space operations, and more capable of returning some data in the event of fiscal or political changes. NASA also canceled or deferred some sensors that were either unlikely to be ready for launch on either of the frost two satellites in the EOS series or too costly to include in the reduced funding profile.

In passing the fiscal year 1993 NASA appropriations, Congress further reduced NASA's future funding expectations for EOS by an additional $3 billion, an action consistent with NASA's efforts to reduce the costs of large programs. Between fiscal years 1991 and 2000, NASA can now expect to spend $8 billion for EOS "exclusive of construction of facility, launch, and tracking requirements, but including the Earth Observing System Data and Information System (EOSDIS).[10] NASA has revised its restructured EOS program to account for this projected funding level (box 5-C). As a consequence, NASA has reduced most of the contingency funds, exposing the program to the risk that it will be unable to complete some instruments or may have to cut back on their capacity to acquire certain data.

Additional large budget cut-backs may be difficult to absorb; a third major restructuring might result in the loss of several instruments. Tight budgets have also precluded the development of system backups; this lack of redundancy is an additional risk to the EOS program. The existing $8 billion program is probably not the program NASA would have designed if it had begun planning EOS with such a budget in mind. In fact, some scientists have suggested that by planning a $17 billion program and Scaling back in accordance with congressional and administration concerns over the future space budget, NASA will be less effective in collecting data for global change research. Nevertheless, the second restructuring still emphasizes the collection of data on climate change, which is the highest priority of the USGCRP. If Congress wishes to continue a U.S. emphasis on global change research, it should support the development of Mission to Planet Earth at a level sufficient to accomplish the science objectives of the U.S. Global

[9] The reduction in platform size, which was strongly recommended in the "Report of the Earth Observing System (EOS) Engineering Review Committee,' allows a reduction in the size and cost of the launch vehicles needed to boost these satellites to space. However, the overall cost for the same data may well be higher compared to the original plan that used fewer, larger platforms.

[10] U.S. Senate, Committee on Appropriations, "Departments of Veterans Affairs and Housing and Urban Development, and Independent Agencies Appropriation Bill, 1993," report to accompany H.R. 5679, 102-356, July 23, 1992, pp. 145-147.

Box 5-C-The Revised, Restructured EOS Program (1993)

In revising the EOS program from its restructured expected funding level of$11 billion to $8 billion over the decade from 1991-2000, NASA:

- Reduced the amount of contingency available for handling unexpected problems in instrument development and changes in the science requirements. This has the effect of increasing the financial and technical risk to the program, but it maintains the core instruments on the EOS AM and PM platforms.
- Further increased cooperation with European and Japanese partners in EOS. While this spreads the development burden, it also increases the amount of international program coordination required. It also reduces U.S. influence over the development process. For example, the United States will leave to its partners the development of advanced instruments for active microwave sensing.
- Canceled the proposed LAWS and EOS SAR instruments, deferred HIRIS, and moderately descoped other proposed instruments.
- Reduced the amount of EOSDIS funding by 30 percent, which forced reductions in the number of EOSDIS products available to researchers.

SOURCE: "Adapting the Earth Observing System to the Projected $8 Billion Budget: Recommendations from the EOS Investigators," Berrien Moore III, and Jeff Dozier, eds, Oct. 14,1992. Manuscript.

Change Research Program. Although NASA was able to absorb substantial reductions of its proposed long term EOS budget by deferring several expensive instruments and concentrating on climate research, additional major cuts in NASA's MTPE budget could sharply reduce the effectiveness of NASA's research.

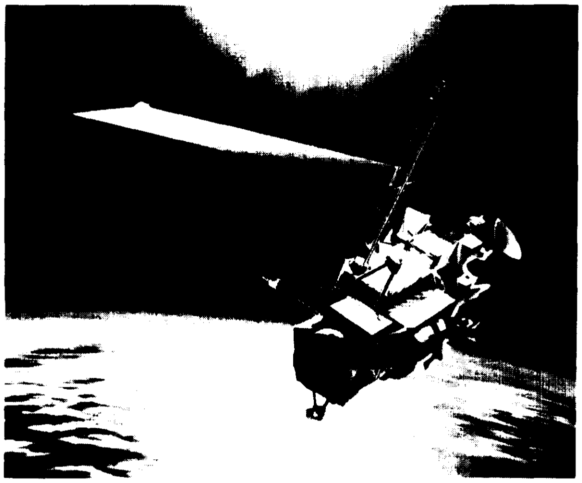
As noted above, the restructuring of EOS has shifted NASA priorities and affected instrument selection. As a result:

- NASA has reemphasized measurements of upper atmospheric chemistry in the belief that data from existing satellites such as the Upper Atmosphere Research Satellite (UARS —figure 5-3), supplemented by planned Shuttle ATLAS missions and in-situ airborne and balloon measurements, will be sufficient to monitor ozone depletion and assess the effectiveness of congressionally mandated phase-outs of chlorofluorocarbons (CFCS). NASA has no plans to launch a satellite designed to acquire equivalent data after UARS fails.[11] However, continued satellite measurements will be needed to monitor the health of Earth's protective ozone layer, to guard against scientific surprises, and to provide the necessary scientific rationale for international protocols that limit emissions of ozone-depleting gases. Long-term information about the state of the ozone layer will be particularly important for developing nations where the relative cost of limiting CFC emissions may be highest. NASA intends to provide some of the necessary data with its TOMS instruments.
- Some relatively inexpensive, small satellite projects are threatened with delay or cancellation—for example, the Active Cavity Radiometer Irradiance Monitor (ACRIM),[12] which would be used to continue measurements to monitor the variability of total solar irradiance, may not fly until 2002. Similar concerns exist for SAGE, an instrument designed to monitor tropospheric aerosols. NASA has dropped other advanced technology instruments because of a reduced emphasis on atmospheric chemistry research. Some researchers express concern that in canceling these instruments, the United States will lose the opportunity to make important climate measurements and risk

11 UARS' planned operation may extend through 1994. Individual instruments and components may fail earlier.

12 On earlier flights of ACRIM.

Figure 5-3-Artist's Conception of NASA's Upper Atmosphere Research Satellite



SOURCE: Martin Marietta Astro Space.

reductions in the U.S. technology base for developing advanced instruments.

- NASA has cancelled three important proposed instruments: Laser Atmospheric Wind Sounder (LAWS),[13] Synthetic Aperture Radar (SAR),[14] and High Resolution Imaging Spectrometer (HIRIS).[15] All are technically challenging and very expensive to develop.[16] All are also "facility" instruments that would acquire data of interest to a large number of investigators.

Although the technical complexity and challenge of the original EOS program, along with the lack of available funds, has forced many of these changes, data from these instruments would make significant contributions to our understanding of the Earth as an interactive system and of global change. If further research demonstrates that these or similar instruments are needed to support additional progress in understanding global change, Congress may wish, before the end of the century, to consider supplemental funding for their development.

In the meantime, NASA should continue to develop technology and scientific research related to these technologies and find ways to reduce system costs. Increased cooperation with the DOE-operated national laboratories offers a particularly attractive mechanism to develop the technology base that will be required **for next-generation sensors and spacecraft.** Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratories, in particular, have considerable expertise in spacecraft instrument design. DOE has proposed collaborative projects focusing on the acquisition of data about Earth's radiation budget, an important component of DOE's Atmospheric Radiation Measurement (ARM) program. They have also proposed collaborative projects to develop hyperspectral sensing that could be mounted on satellites or aircraft (the DoD also has an aircraft-based program to develop hyperspectral sensors-' 'HYDICE' ').

International cooperation can offer a means to increase the capability of collecting important environmental data while reducing costs for any single government. In order to ease its own cost burden for sensors and satellite systems while maintaining the capability to monitor important features of Earth's environment, NASA has reduced funding for certain sensors and enhanced its cooperative remote sensing programs with other countries. Japan and the European Space Agency are being asked to take on the development of several sensors that would fly on U.S. spacecraft and to provide space on their spacecraft for U.S. sensors. However, international cooperative arrangements can only fill part of the void left by the rapid restructure of EOS. Some of

13 For direct measurement of tropospheric winds at high resolution.

14 For making hi@ resolution radar images of land, ocean, and ice surfaces.

15 For&g high spatial resolution images of Earth's surface in some 200 contiguous, very narrow infrared and visible spectral reds.

16 See app. B fo, a more extensive discussion of these instruments and their development.

Table 5-2—The Current EOS Spacecraft Program

Launch	Spacecraft	Lifetime (yrs)	Instrument complement					
1998	AM1	5	MODIS	MISR	CERES (2)	MOPITT	ASTER	
2003	AM2	5	MODIS	MISR	CERES	EOSP	TES	MOPITT*
2008	AM3	5	MODIS	MISR	CERES	EOSO	TES	
1988	COLOR	3	SeaWiFS-Type					
2000	AERO1	3	SAGE III					
2003	AERO2	3	SAGE III					
2006	AERO3	3	SAGE III					
2009	AERO4	3	SAGE III					
2012	AERO5	3	SAGE III					
2000	PM1	5	MODIS	AMSU	MIMR	AIRS	MHS	CERES (2)
2005	PM2	5	MODIS	AMSU	MIMR	AIRS	MHS	CERES
2010	PM3	5	MODIS	AMSU	MIMR	AIRS	MHS	CERES
2002	ALT1	5	GLAS	TMR	SSALT	DORIS		
2007	ALT2	5	GLAS	TMR	SSALT	DORIS		
2012	ALT3	5	GLAS	TMR	SSALT	DORIS		
2002	CHEM1	5	HIRDLS	SOLSTICE II	ACRIM	MLS	SAGE III	TBD(J)
2007	CHEM2	5	HIRDLS	SOLSTICE II	ACRIM	MLS	SAGE III	TBD(J)
2012	CHEM3	5	HIRDLS	SOLSTICE II	ACRIM	MLS	SAGE III	TBD(J)

SOURCE: 1993 EOS Reference Handbook, EOS Program Chronology.

the scientific objectives must be deferred until new domestic or foreign funding sources are made available.

Increased international cooperation in remote sensing is possible because over the past decade other countries have markedly improved their skills in sensor development and satellite systems integration and construction. Canada, France, Germany, the United Kingdom, Japan, Russia, China, and India have made satellite remote sensing a priority. Prospects **for greater international cooperation will increase as the remote sensing programs of other countries grow in technical breadth and capability.**

Some policymakers express the concern that increased cooperation will boost the technical capabilities of other countries by giving foreign industry a chance to develop technology in which the United States has a strong lead. In addition, because foreign experience with some systems is less well developed than that of U.S. industry, some scientists fear sensors developed abroad might be less capable than ones built domestically, leading to incomplete data sets. Hence, in **order to ensure that the United States does not forfeit the lead in technical capabilities it considers vital to national competitiveness, Congress may wish to scrutinize closely the structure of any international agreements in remote sensing.**

Another problem with international cooperation is that each country has a strong interest in providing the most advanced instruments or systems. The outcome is that a cheap, simple satellite design can quickly grow into a relatively expensive, complex system.

NASA expects to operate EOS and EOSDIS for at least 15 years after the launch of the second major satellite (PM-1) in 2000 (table 5-2). Therefore, the program will necessarily take on the characteristics of what has been called an 'operational program'—in other words, sustained, routine acquisition of data that must be routinely available to researchers and other users on a timely basis. To **achieve maximum effectiveness, NASA's EOS Program must be organized and operated with great attention to the regular, timely delivery of data. This** means, for example, not only that EOSDIS (box 5-D) function smoothly, and in a "user friendly" manner, but that the sensor systems that feed data into EOSDIS are prepared to deliver vast amounts of data with few processing errors or system slowdowns.

STRUCTURING A ROBUST RESPONSIVE, GLOBAL CHANGE RESEARCH PROGRAM

NASA plans to use EOS to provide scientists with data relevant to questions that often polarize public debate regarding climate change and its global environmental effects. Although these data may help resolve some contentious scientific issues, **they may not** produce results that lead to clearcut policy decisions. Data from instruments aboard EOS and other satellites, as well as from many other sources, will be used to study the effects of global change and to predict possible future changes in Earth's environment. Unlike the recent observations of ozone-destroying chlorine molecules in the upper atmosphere, which quickly led to a speedup in the phase-out of U.S. chlorofluorocarbon (CFC) production, few of the research questions that can be addressed by the USGCRP will result in straightforward policy responses. Most of these data will provide inputs to complex models intended to predict future climatic and environmental conditions. Because of the complexity of the models, finding sufficient scientific agreement to draw definitive conclusions for policymakers to act on may be especially difficult. Although scientific research may provide evidence linking the production of particular gases to deleterious climate changes, predicting regional environmental changes that could signal major economic disruptions may not be possible for decades. Moreover, even when the facts are known and the processes understood, proposed solutions may not necessarily be clear or uncontentious. However, the best chance the United **States has to develop the scientific basis for good policy is to pursue the best science, based on a robust, responsive global change research program. Such a program would include a strong commitment to making observations from instruments based in aircraft, ships, and ground facilities, as well as from space.**

| Existing Satellite Systems

Most existing space-based remote sensing instruments contribute in some way to global change research-NOAA's environmental satellites, the Landsat system, and NASA's research satellites. For example, the polar-orbiting NOAA POES satellites (box 3-D) carry the High Resolution Infrared Radiation Sounder (HIRS) and the Microwave Sounding Unit (MSU), which daily measure atmospheric temperature and humidity, and the Advanced Very High Resolution Radiometer (AVHRR), which can be used to monitor the global state of vegetation, the extent of Arctic and Antarctic ice pack, and sea surface temperatures. Observations from both instruments contribute to research on global change. In general, NOAA instruments provide the long-term data sets necessary for identfying previous trends (plate 9). However, because the instruments **in NOAA's environmental satellites were designed to serve NOAA's needs in collecting weather and climate data, these instruments lack the necessary calibration to gather precise data required for sensing and interpreting subtle, gradual changes in the environment. Sensors aboard future NOAA satellites ought to be designed to provide data having better calibration.**[17]

Remotely sensed data from Landsat, SPOT, ERS-1, JERS-1, and other satellites optimized for imaging surface features will become increasingly important in following local, regional, and global environmental change (plate 7). Landsat and SPOT have contributed significant quantities

17 Providing better calibration will add to the cost of the sensors, however.

Box 5-D—Earth Observing System Data and Information System

EOSDIS will consist of 8 interlined Distributed Active Archive Centers (DAACS) and a Socioeconomic Data and Applications Center (SEDAC) that will archive original data, create scientific data products, and make them available to users either at t he centers or on line. NASA plans to spend about $1.5 billion on the development and operation of EOSDIS. This investment will result in a large number of data sets that can be accessed repeatedly by various users. Handling large data sets in an open network presents many challenges, and will push the state of the art in software and communications hardware. EOSDIS will be the key link between the data collected by the satellite systems and the scientists working on global change research.

EOSDIS will challenge NASA's technical and organizational skills in part because the system and its data products cannot be well-defined at this early stage. The data storage and retrieval system will require new image processing techniques capable of handling interrelated data sets, and a transparent "window" for the user. The system must be able to run in multiple operating environments, and be accessible by people possessing different levels of computer skills. EOSDIS will require innovative solutions to data handling that will take years to develop. EOSDIS will also require improved data compression and decompression algorithms. These compression schemes must work at extremely fast data rates, yet not degrade data integrity. Maintaining the data securely is a priority for any large data system, and it will be extremely challenging for an EOSDIS that will be open to hundreds and eventually thousands of users.

If EOS data can reduce scientific uncertainty surrounding atmospheric and environmental changes, the program will be a success. A successful EOS will depend largely on the ability of EOSDIS designers and managers to create a system in which massive amounts of data can be archived, cataloged, maintained, and made routinely accessible to users, and which will maintain the integrity of the data.

NASA's first objective is to expand the amount of earth science data available to the scientists. With help from the science user community, it has identified large, "pathfinder," data sets for inclusion in EOSDIS Version O. Pathfinder sets will include data that have been collected over many years by operational satellites such as NOAA polar orbiters and geostationary satellites and Landsat. EOSDIS will serve as the archive for these data sets, which will assist global change researchers and allow NASA contractors gradually to improve EOSDIS based on experiences of initial users. According to t he General Accounting Office, progress on gathering and reprocessing pathfinder data has been slow.[1] Only one complete data set is expected to be available by 1994, and only three complete data sets will be available by 1996. Slow progress on pathfinder data sets may impede planning and development for latter phases of EOSDIS.

[1] U.S. Congress, General Accounting Office, "Earth Observing System: Information on NASA's Incorporation of Existing Data Into EOSDIS," September 1992.

SOURCE: Office of Technology Assessment, 1993.

of high-quality data to archives that can be used to provide early indications of harmful change in localized areas.[18] Existing data, especially those being prepared under the Pathfinder EOSDIS efforts, need to be studied in detail to understand better how to use remotely sensed land data in global change studies.

Small Satellites

As instruments aboard satellite svstems irnprove, they are likely to assist in the development of much needed information about the global environment and how it is changing. However, as currently structured, satellite systems may not provide some of the most urgently needed data

[18] See Matthew D. Cross, *Historical Landsat Data Comparisons: Illustrations of Land Surface Change* (Washington, DC: U.S. Geological Survey, 1993), for a sample of the surface changes that Landsat data are capable of revealing. Because these digital data can be readily sorted and manipulated in a computer, and merged with other data, they can be used to make quantitative estimates of change.

in time to assist the policy debate. In addition, the United States has no plans for monitoring aspects of global change on decadal timescales. Yet, many climatologists and other scientists believe that monitoring on this timescale will be essential to 1) build databases over sufficiently long periods to support global change research and refine predictive models, and 2) monitor the often subtle climatic and ecological changes induced by anthropogenically produced gases and other pollutants.[19]

Moreover, some researchers argue that the appropriate instrument platforms to carry out ***decadal-scale* measurements are not the large, complex, and expensive satellites planned for the EOS program. These** researchers argue that a balanced program for global change research would include smaller, less expensive, and less complex satellites that would be developed specifically for particular monitoring missions,[20]

Several agencies, including NASA, DOE, and ARPA, are examining the use of small satellites for global change research. Small satellites, which have been defined as costing $100 million or less, including spacecraft, instruments, launch, and operations, could:[21]

- address gaps in long-term monitoring needs prior to the launch of EOS missions,[22]
- provide essential information to support process studies prior to, and complementary with, the restructured EOS,
- allow for innovative experiments to improve the ability to monitor key variables or improve/speed up the process studies.[23]

Matching small instruments with small satellites has several potential advantages: First, it avoids the necessity of integrating multiple instruments on a single platform-this simplifies the acquisition process, albeit at a possibly higher overall cost. Second, shortening the time to launch would add resilience to the satellite portion of the global change research program, large parts of which are frozen in development some 10 years before flight. Third, flying only a small number of instruments per satellite allows scientists to optimize the satellite orbit for a particular set of measurements.[24] Finally, flying small instruments on small satellites increases the likelihood that a small core of key environmental sensors can:

- be launched before the EOS system and thus prevent data gaps that would otherwise be created in the mid-to-late 1990s (before EOS launches);
- be maintained even if EOS suffers further cutbacks; and
- be maintained for years beyond the scheduled 15-year lifetime of the EOS system.

However, the funding for such satellites would have to come from some other source than the EOS program, Otherwise, the deployment of the first EOS satellites (AM-1998; PM—2000) would risk being delayed.

Global change researchers express widespread agreement on the desirability of using small satellites for these three roles. However, scientists express sharp disagreements about the long-term

19 For example, the burning of fossil fuels, use of CFCS, and agriculture.

20 Liz Tucci, "EOS Backers Push for Faster Launches, " *Space News*, Mar. *29, 1993,* p. 14.

21 See Committee o_n Earth and Environmental Sciences (CEES) of the Federal Coordinating Council for Science, Engineering, and Techr.ology, *Report of the Small Climate Satellites Workshop* (Washington DC: Office of Science and Technology Policy, May 1992).

22 Gap-filling spacecraft were initially proposed in 1991. With the frost EOS launch scheduled fOr 1998, the opportunity for using these spacecraft is fast drawing to a close.

23 *Report of the Small Climate Satellites Workshop*, pp. 20-21. As noted in the text, researchers at the Goddard Institute for Space Studies have also proposed using small satellites for long-term (decadal-scale) monitoring in a program that would complement EOS.

24 S_ome fissions require nearly simultaneous measurements by instruments that cannot be packaged on a single, small satellite. In this case, a larger platform carrying several instruments may be desirable. Alternatively, small satellites could be flown in close formation.

potential for small satellites to replace larger, more expensive satellites such as Landsat. Advocates of small satellites believe satellite weight and volume can be reduced by incorporating advanced technologies, now in development, with next generation spacecraft. However, proposed new instrument technologies are typically at an early stage of development and their capability to provide the stable, calibrated measurements required for global change research is likely to be unproved, Stability and calibration requirements are particularly important for long-term monitoring. Fully developed data processing systems and well-understood data reduction algorithms are also required to transform raw data into useful information.[25]

Historically, satellite designers have minimized risk by introducing advanced technology in an evolutionary manner; typically, only after it has been proven in the laboratory and acquired a heritage of space worthiness. Although experts generally agree on the desirability of accelerating this relatively slow process, they do not agree on the risk that would be associated with a change in the traditional development cycle.[26] The risks in developing **a new sensor system have two components: the technical maturity of component technologies (for example, the detector system), and the design maturity. A particular design that has not been used before may be a relatively risky venture for an operational program, even if it is based on proven technology.** Several proposals have been made to reduce the risks of inserting new technologies into operational programs. Box 5-E summarizes one example from the Advanced Research Projects Agency.

Box 5-E-The Advanced Research Projects Agency CAMEO Program

ARPA has proposed several advanced technology demonstrations (ATDs) on small satellites that, if successful, would rapidly insert technology and shorten acquisition time for larger satellites.' These demonstrations would couple innovative sensor design with a scalable high-performance common satellite bus that would employ a novel "bolt-on" payload-bus interface. ARPA-proposed ATDs include ATSSB (advanced technology standard satellite bus) and CAMEO (collaboration on advanced multi-spectral Earth observation). They were fully supported by the Department of Defense, but were eliminated by the Senate Appropriations Committee for fiscal year 1993.

l See **app. B for more detail on this proposal.**

SOURCE: Advanced Research Projects Agency, 1993.

To date, budget constraints, scientific disputes over the merits of specific proposals, intra-agency and inter-agency rivalries, and the absence of a coherent strategy, developed within the executive branch and supported by the relevant authorization and appropriation committees **of Congress, has limited efforts to develop and flight-test emerging technologies.** Appendix B discusses these issues at greater length along with specific proposals for launching small EOS satellites. Appendix B also notes that the development of innovative, lightweight sensors appropriate for small satellites and the development of sensors for long-endurance, high-altitude UAVS share many common features.

25 An illustrative example is given by the complex analysis that is required to measure the Earth's radiation budget (see app. B).

26 A phased development cycle has traditionally been used to procure operational systems. The Steps in this cycle can be grouped as follows:

Phase A—Study Alternate Concepts;

Phase B—Perform Detailed Design Definition Study (manufacturing concerns addressed in this stage);

Phase C—Select Best Approach/Build and Test Engineering Model;

Phase D-Build Flight Prototype and Evaluate on Orbit.

This approach should be contrasted with a ''skunk-works' approach, which omits some of these steps. Historically, the skunk-works approach has usually been thought more risky than the methodical approach. As a result, it has been used mostly for demonstrations and experiments.

Box 5-F-Radiative Forcings and Feedbacks

Radiative forcings are changes imposed on the planetary energy balance; radiative feedbacks are changes induced by climate change. Forcings can arise from natural or anthropogenic causes (see table 5-3). For example, the concentration of sulfate aerosols in the atmosphere can be altered by both volcanic action (as occurred following the eruption of Mt. Pinatubo in June 1991) or from power generation using fossil fuels. The distinction between forcings and feedbacks is sometimes arbitrary; however, scientists generally refer to forcings as quantities that are normally specified, for example, CO_2 amount, while feedbacks are calculated quantities. Examples of radiative forcings are greenhouse gases (CO_2, CH_4, CFCS, N_20, OS, stratospheric H_20), aerosols in the troposphere and stratosphere, solar irradiance, and solar reflectivity. Radiative feedbacks include clouds, water vapor in the troposphere, sea-ice cover, and snow cover.

SOURCE: office of Technology Assessment, 1993 and Dr. James Hansen, Goddard Institute for Space Studies.

Climsat

Present and future global climate change cannot be interpreted without knowledge of changes in climate forcings and feedbacks (box 5-F). "Climsat" is the name of a proposed system of environmental satellites that would carry out long-term monitoring of the Earth's spectra of reflected solar and emitted thermal radiation. Climsat satellites would be flown in pairs, one in polar and the other in inclined orbit.[27] Each would carry three small, lightweight instruments (see box 5-G). Climsat satellites would be self-calibrating,[28] small enough to be orbited with a Pegasus-class launcher,[29] long-lived (nominally 10 years or more), and relatively inexpensive.[30] The originators of the Climsat proposal believe it could provide most of the missing data required to analyze the global thermal energy cycle, specifically long-term monitoring of key global climate forcings and feedbacks. In addition, proponents claim Climsat would be a more "resilient" system than EOS because it would launch a small complement of relatively inexpensive instruments on small satellites. However, Climsat alone is not intended to fulfill the broader objectives of the Mission to Planet Earth and the Earth Observing System Program.

Monitoring of global radiative forcings and feedbacks is essential to understanding the causes, time-scale, and magnitude of potential long-term changes in global temperature. However, a program to correlate changes in average temperature with changes in radiative forcings and feedbacks is expected to require measurements that would extend over decades. Unlike EOS satellites, which NASA proposes to fly for a total of 15 years, Climsat satellites would be operated for several decades.[31]

27 As described in the text, two satellites are specified in the Climsat proposal because this number is necessary for global COverage and adequate sampling of diurnal variations.

28 SAGE calibration is obtained by viewing the sun (or moon) just before or after every occultation. MINT records its interferogram on a single detector and therefore would have high wavelength-to-wavelength precision. EOSP interchanges the roles of its detector pairs periodically. Stable internal lamps are used for radiance calibration.

29 A launch on Pegasus costs about $10-12 million. Pegasus can carry payloads weighing up to 900 pounds.

30 Cost estimates are uncertain at an early stage of concept definition. However, two of the three Climsat instruments have gone through phase A/B studies in EOS, leading Goddard Institute of Space Studies researchers to make the following estimates:

SAGE III-$34 million for 3 EOS copies (18 million for first copy);
EOSP—$28 million for 3 EOS copies ($16 million for first copy);
MINT—$15-20 million for first copy.

31 EOS officials agree that decadal-scale monitoring of the Earth is needed; they foresee some subset of EOS instruments evolving into operational satellites designed for long-term monitoring.

Table 5-3-Human Influence On Climate

Fossil fuel combustion
- CO_2 emission (infrared (IR) trapping).
- CH_4 emission by natural gas leakage (IR trapping).
- NO, NO_2 emission alters O_3 (ultraviolet absorption and IR trapping).
- Carbonaceous soot emission (efficient solar absorption).
- SO_2-Sulfate emission (solar reflection and IR trapping).

Land use changes
- Deforestation (releases CO_2 and increases surface albedo)
- Regrowth (absorbs CO_2 and decreases surface albedo).
- Biomass burning (releases CO_2, NO, NO_2, and aerosols).

Agricultural activity
- Releases CH_4 (IR trapping).
- Releases N_2O (IR trapping).

Industrial activity
- Releases CFCs (IR trapping and leads to ozone destruction).
- Releases SF_6, CF_4, and other ultra-longlived gases (IR trapping virtually forever).

KEY: CF_4 = carbon tetrafluoride; CO_2 = carbon dioxide; CH_4 = methane; NO = nitric oxide; NO_2 = nitrogen dioxide; N_2O = nitrous oxide; O_3 = ozone; SO_2 = sulfur dioxide; SF_6 = sulfur hexafluoride; CFCs = chlorofluorocarbons.

SOURCE: Jerry D. Mahlman, "Understanding Climate Change," Draft Theme Paper, prepared for Climate Research Needs Workshop, Mohonk Mountain House, Nov. 8, 1991.

Both the initial EOS program and the initial Climsat proposal have been revised since their initial presentations. Versions of two of the three Climsat instruments are now scheduled for flight on later EOS missions. However, Climsat supporters argue that flying these instruments as part of Climsat would:

- allow flight in proper orbits;
- guarantee overlapping operations (over longer periods), which would result in better calibrated measurements;
- allow launch several years before the relevant EOS platforms;[32] and
- allow instrument modification on a shorter time-scale than EOS instruments and thus be better able to respond to scientific surprises.

Supporters also argue that Climsat instruments are better designed to handle scientific surprises because:

- unlike related larger instruments on EOS, they cover practically the entire reflected solar and emitted thermal spectra, and
- the Climsat instruments measure the polarization as well as the mean intensity of the solar spectrum where polarization is highly diagnostic of the observed scene.

A key argument in favor of the Climsat proposal is its potential to carry out a core group of key remote sensing measurements on a decadal time-scale. In effect, supporters of Climsat argue that the data that would be gathered by Climsat—or a similar system-is too important to be tied to the budgetary fate and schedule of EOS. Detractors of the Climsat proposal include those who believe that its funding could come only at the detriment of an already diminished EOS program. Further, they contend that Climsat addresses only a narrow part of the climate problem. For example, they question whether data from Climsat are, in fact, more important than data on ocean color, land-surface productivity, atmospheric temperature and humidity, and snow and ice volume.

Complementing Satellite Measurements

Satellites alone cannot carry out a robust program of global change research, Orbiting above the atmosphere, a satellite remote sensing system receives information about atmospheric or terrestrial processes only via electromagnetic signals reflected or emitted from the atmosphere or the surface. Sensors collect these signals and transform them into forms that can be used as input data for analysis and interpretation. Scientists need to compare satellite data with surface-based or airborne measurements to verify that the satellite data are free of unforeseen instrument

32 Dr. James Hansen, developer of the Climsat proposal, estimates that the Climsat satellite would require 3 years to build and launch after approval and procurement processes are complete.

Box 5-G - The Data Storage Problem

The sheer size of archives for remotely sensed Earth data can be estimated through some simple calculations. The data storage requirement is the product of the storage needed for each pixel and the number of pixels. Such a calculation is done in terms of "bits," the O's and 1's used in computers' binary arithmetic.

As an example, consider an Earth's worth of Landsat-like pictures from a notional satellite with 10 bands, each imaging 25- X 25-meter pixels in terms of 32 brightness levels. The 32 gradations of brightness are expressed by 5 bits, so each square kilometer, consisting of 1,800 pixels, requires 1,800X 10X 5 = 80,000 bits, or 10 kilobytes. (For comparison's sake, this box requires about 2 kilobytes of computer storage.) The Earth's 200 million square kilometers of land, therefore, would require 2 billion kilobytes of storage capacity.

Two billion kilobytes is roughly the storage capacity of 20 million late-model home computers or 3,000 compact disc recordings.

The Human Genome Project, to take another example of data collection and storage, will not have to deal with nearly this much data. The genome consists of 3.3 billion base pairs, each embodying 1 bit. Thus the genome is "only" 3,300 megabits, or about 400 megabytes-about the contents of half a compact disc.

To observe change, or the most current situation, further pictures are needed and must be stored. Each adds another 2 billion kilobytes. Inclusion of the water-covered three-quarters of the Earth's surface would increase the size of each picture to 8 billion kilobytes, and "hyperspectral" techniques, involving 100 bands instead of 10, would increase storage needs an additional tenfold.

SOURCE: office of Technology Aseeesment, 1993.

artifacts or unforeseen changes in instrument calibration. These comparisons are particularly important for long-term measurements and for measurements that seek to measure subtle changes. Satellite data must also be corrected to account for the attenuation and scattering of electromagnetic radiation as it passes through the Earth's atmosphere. In addition, corrections are necessary to account for the variations in signal that occur as a result of changes in satellite viewing angle. Nonsatellite data can also assist in the analysis of satellite data by clarifying ambiguities in the analysis and confirming certain measurements. Finally, sensors on satellites may be limited in their capability to make measurements in the lower atmosphere, and they may be unable to make the detailed measurements required for certain process studies.

Balloons and aircraft are generally more "responsive" than satellites: in general, an experiment to monitor a specific process can be mounted faster on an aircraft or balloon experiment than on a satellite. Furthermore, as noted earlier, the development of instrumentation on airborne platforms greatly assists the development of space-qualified instrumentation for satellites. However, balloons and aircraft cannot be used for monitoring global phenomena that have small-scale variability because their coverage is limited in time (intermittent coverage, weather restrictions) and space (altitude ceilings, geographic restrictions).

Process Studies and Unpiloted Air Vehicles

"Process"3[3] studies, which are necessary to understand global forcings and feedbacks in detail, require ground and in situ measurements. For example, a detailed understanding of the kinetics and photochemistry that govern the formation of the Antarctic ozone hole (and the

33 There is no clear delineation between "process" studies and monitoring studies. In general, global change researchers use the term ''process study' to refer to shorter term, less costly, and more focused experiments that aim to elucidate the details of a particular mechanism of some geophysical, chemical, or biological interaction.

role of the Antarctic vortex) has only been possible with in situ balloon and high-altitude aircraft measurements.[34] Development of high altitude unpiloted aircraft would extend these measurements, which would be especially useful in elucidating the mechanisms that cause significant loss of ozone over the Arctic and northern latitudes.

High-altitude unpiloted air vehicles (UAVS) offer significant advantages over satellites for measuring some upper atmospheric constituents. In particular, they can be used for accurate in situ measurements-actually sampling the constituents of the upper atmosphere and using the samples to decipher, for example, the chemical reactions taking place among stratospheric ozone, chlorine monoxide, bromine monoxide and other man-made substances. Because instruments on UAVS can be changed or adjusted after each flight, UAVS are also potentially more responsive than satellite systems to new directions in research or to scientific surprises. Unlike balloons, they move through the air, rather than with it, allowing operators to guide their paths.

In addition to its use of high-altitude balloons and piloted aircraft, NASA plans to employ a small UAV called *Perseus,* developed by the small private firm, Aurora Flight Services, Inc.[35] for atmospheric studies. The first two *Perseus* aircraft *(Perseus A) are* scheduled for delivery to NASA at a cost of about $1.5 to $1.7 million each. NASA will initially use sensors carried on *Perseus* to determine the chemistry and movement of gases in the stratosphere at altitudes up to approximately 25 kilometers (82,000 feet).

UAVS may provide global change researchers with low-cost and routine access to regions of the atmosphere that are inaccessible to piloted aircraft, sampled too infrequently by balloon, and sampled too coarsely by satellites. UAVS should also be highly cost effective in providing crucial in situ measurements of atmospheric chemical constituents. They are also a natural test-bed for small, lightweight instruments proposed for flight on small satellites. Despite their potential to enable measurements that are crucial **for the global change research program, government support for UAV development, and associated instrumentation, has been meager and may be inadequate to provide a robust UAV capability. If Congress wishes to encourage innovation in global change research, it may wish to increase funding for UAVS.** Because of their low development costs, moderate funding increases of only a few million dollars could ultimately lead to a substantial increase in UAV availability for research.[36]

Satellites view the Earth only from above the atmosphere; this limits their measurement of two physical quantities of interest to global change research. One, the angular distribution of radiation, is necessary for measurements of Earth's radiation budget.[37] The other, the ''flux divergence, ' can be related to the net heating that occurs in a particular layer of the atmosphere. It is a fundamental parameter in global circulation models of Earth's atmosphere and climate. UAVS are ideally suited to make these measurements and would complement groundbased observa-

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34 J.G. Anderson, D.W. Toohey, W.H. Brune, ''Free Radicals Within the Antarctic Vortex: The Role of CFCS in Antarctic Ozone Loss,'' *Science,* vol. **251,** Jan. 4, 1991, pp. 39-46.

35 Richard Monastersky, ' 'Voyage Into Unknown Skies, *Science News,* vol.139, Mar. 2, 1991, pp. 136-37; Michael A. Dornheim, ''Perseus High-Altitude Drone to Probe Stratosphere for SST Feasibility Studies, " *Aviation Week and Space Technology,* Dec. 9, 1991, pp. 36-37.

36 NASA is now asking for additional funding of $90 million over 5 years to build and fly UAVs for scientific research.

37 The Earth's ''radiation budget' consists of incident sunlight minus reflected sunlight (for example, from the tops of clouds) and radiation emitted back to space, primarily from Earth's surface and atmosphere. The emitted radiation falls predominantly in the infrared and far-infrared portion of the electromagnetic spectrum. Earth's average temperature rises or falls to keep the total incoming and outgoing energy equal. Changes in the amount of energy entering or leaving Earth result in global warming or cooling.

tions made in the Department of Energy's atmospheric radiation program (ARM).[38]

Groundbased observations in DOE's ARM program also provide an important source of calibration data for space-based observations of atmospheric solar heating. Likewise, NOAA'S proposed Telesonde program,[39] a groundbased system integrating high-quality measurements of atmospheric winds, temperature, and moisture, would serve to calibrate satellite measurements in portions of the atmosphere in which measurements of the satellite and groundbased instruments overlap.

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38 U.S. Department of Energy, Office of Health and Environmental Research, *Atmospheric Radiation Measurement Unmanned Aerospace Vehicle and Satellite Program Plan*, March 1992 draft (Washington, DC: Department of Energy, March 1992). Also see Peter Banks et. al., *Small Satellites and RPAs in Global-Change Research,* JASON Study JSR-91-33 (McLean, VA: JASON Program Office, The MITRE Corp., July 13, 1992).

39 "Management Information," Wave Propagation Laboratory, National Oceanic and Atmospheric Administration, October 1990.