The EOS Program 3

The Earth Observing System (EOS), the space-based component of NASA's Mission to Planet Earth (MTPE), is a series of polar-orbiting and low-inclination satellites to enable global observations of the land surface, biosphere,[1] solid Earth, atmosphere, and oceans. EOS is a central element of the U.S. Global Change Research Program (USGCRP). It is being executed by NASA as per National Space Policy Directive-7,[2]

This chapter draws on the OTA workshop to address questions related to EOS in three general areas:

1. the scientific priorities of the program;
2. the process that sets and reviews these priorities; and
3. the "balance" in the program between a) detailed studies of Earth processes and long-term monitoring, and b) ground- and air-based methods of data acquisition versus satellite-based methods.

Participants at the OTA workshop were asked a number of specific questions in these issue areas (see app. A).

THE EVOLUTION OF THE EOS PROGRAM

The principal EOS spacecraft for sensors gathering global change data are intermediate-size, multi-instrument, polar-

[1] The biosphere is the portion of the Earth and its atmosphere that can support life. Studies of the biosphere are frequently linked to studies of that part of the global carbon cycle which involves living organisms and life-derived organic matter.

[2] NSPD-7, authorized by then President George Bush in 1992, assigns to NASA the lead role in enabling global observations from space.

orbiting satellites.[3] To achieve continuous 15-year data sets, NASA plans three launches of two EOS platforms-'' AM" and "PM," indicating morning or afternoon crossing over the equator—each of which has a design life of 5 years.[4] An observation period of 15 years is long enough to observe the effects of climate change due to one sunspot cycle (11 years), several El Nino events, and perhaps the eruption of one or more major volcanoes. It should also be possible to observe some effects of deforestation and other large-scale environmental changes.

Scientists are less certain whether another 15 years of measurements will be sufficient to allow the effects of anthropogenic greenhouse gases (those that result from human activities) on Earth's temperature to be distinguished from natural background fluctuations.[5] Ecological studies of the health and migration of terrestrial systems require even longer continuous records—on the order of 20 to 50 years. As discussed below, scientists disagree on whether the EOS program currently planned will evolve into a system appropriate for such long-term monitoring.

NASA originally conceived of EOS as a program to understand Earth systems by making abroad range of environmental and Earth science measurements. In effect, the program sought to use the vantage point of space to measure as many of the variables of interest to Earth scientists as possible.[6] When NASA initiated the program in 1989, it envisioned flying 30 instruments—representing many of the Earth sciences and some Earth-related solar science-on two large spacecraft in polar orbit. The program initially had an estimated total cost of $17 billion for fiscal year (FY) 1991 through FY 2000 and involved the use of large Titan IV launch vehicles.

NASA restructured EOS in early 1992 to a program whose cost through FY 2000 would be approximately $11 billion.[7] However, EOS underwent a second revision after the FY 1993 appropriation because Congress placed a ceiling on the decadal funding of EOS of approximately $8 billion, all of the $3 billion reduction to be absorbed between FY 1994 and 2000. The nearly 30-percent funding reduction from $11 billion was also consistent with the objectives of a review ordered by NASA Administrator Daniel Goldin.

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[3] EOS polar orbiters are termed ''intermediate-size' by program officials because they arc smaller than the very large satellites envisioned in the initial EOS proposal. By most standards, they are still large and expensive. For example, NASA estimates that total hardware development costs for the EOS AM-1 satellite and its sensors will approach $800 million. This figure does not include launch costs of $100 to 150 million (AM-1 requires an Atlas IIAS launcher), or ground segment and operations costs.

[4] EOS AM-1 and PM-1 will both be launched in sun-synchronous polar orbits, but with different crossing times. NASA designed the EOS-AM spacecraft primarily to observe terrestrial surface features and thus has a morning crossing time when cloud cover is minimum over land. The EOS-PM platform includes a next-generation atmospheric sounder, which is a candidate for deployment on future NOAA operational satellites, and other climate measuring instruments that are more suited towards art afternoon crossing.

[5] According to the IPCC, the unequivocal detection of an enhanced greenhouse effect is not likely to be observed for another decade or more.

[6] See Shelby G. Tilford, testimony before the Subcommittee on Space of the Committee on Science, Space, and Technology, May 6, 1993. Also see 'Earth Scientists Look NASA's Gift Horse in the Mouth,'' *Science,* vol. 259, No. 5097, Feb. 12, 1993, pp. 912-914 and U.S. Congress, Congressional Research Srevice, *Mission to Planet Earth and the U.S. Global Change Research Program,* CRS-90-300 SPR (Washington, DC: U.S. Government Printing Office, June 19, 1990), pp. 6-11 and references therein.

[7] EOS was restructured in 1992 following recommendations by the EOS Engineering Review Panel, which were also incorporated into a House-Senate conference report. By focusing on climate change instead of the broader issues addressed in the baseline program, NASA was abte to reduce to 17 the number of instruments that needed to fly by 2002. Instead of the original plan to fly two large satellites (EOS-A and EOS-B), these instruments were configured tofty ona several smaller multi-instrument polar orbiters and free flyers: 1) Three intermediate-size spacecraft series to be launched by intermediate-class expendable launch vehicles (EOS-AM, EOS-PM and EOS-CHEM); 2) one smaller spacecraft series to be launched on a medium-class expendable launch vehicle (EOS-ALT); and 3) two small spacecraft series to be launched on small launchers (EOS-COLOR and EOS-AERO).

In restructuring the EOS program, NASA chose to emphasize those global change issues the Committee on Earth and Environmental Sciences (CEES) believed to be most in need of improved scientific understanding. This affected both priorities and instrument selection.[8]

Consistent with the USGCRP, the restructured program's first priority is acquiring data on the global climate. As a result, NASA deferred or canceled programs designed to improve scientific understanding of the middle and upper atmosphere and of solid-Earth geophysics.[9] Satellite-based instruments to measure forest biomass or forest chemistry, both of which might change under climate change, were also eliminated.[10] EOS officials acknowledge that budget cuts have forced reductions in instrument contingency funds, and increased reliance on contributions from agencies other than NASA and on Japanese and European partners. According to NASA, the rescoped program has a higher risk in meeting the science objectives beyond the year 2000 because increased reliance on other agency and international collaborations is assumed, but firm commitments are still being negotiated.[11]

The restructured EOS program creates gaps in some measurement programs and risks loss of data continuity in others (box 3-A). Expected data gaps include:

- discontinuity of 5 to 7 years in most of the atmospheric chemistry measurements after the UARS satellite fails,
- discontinuity in ocean circulation measurements,
- discontinuity in Earth radiation budget experiments, and
- discontinuity in measurements of the vertical distribution of aerosols and ozone (through the SAGE instrument).

Scientists would like continuity in all of these measurements, especially those that require long time series of data to distinguish subtle trends (e.g., changes in solar output). According to NASA, EOS program officials made decisions on which instruments to orbit by weighing the consequences of having gaps in some measurements against the benefits of flying new and important instruments by the end of 1998, a date mandated by Congress.

Setting Priorities

The EOS program supports the overall USGCRP by acquiring and assembling a global database of remote sensing measurements from space. The priorities for acquiring these data conform to the seven science areas identified by USGCRP and the Intergovernmental Panel on Climate Change (IPCC) as key to understanding global climate change (ch. 2).[12] Most OTA workshop participants believed the EOS (and by extension, USGCRP and MTPE) science priorities were ordered correctly to gain a predictive understanding of the Earth system.

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[8] For example, deferral of instruments to monitor solid Earth physics, which includes crustal and ice sheet movements, was based on the relative unimportance of these processes to global climate change—the highest priority of the restructured EOS program.

[9] Elimination of missions that might provide a detailed understanding of the fundamental processes that are causing ozone depletion in the lower stratosphere increases the risk that the nation will be 1) unprepared to respond to future surprises, e.g., ozone loss over the northern hemisphere and 2) unable to implement changes in mitigation strategies. UARS, which has no direct follow-on, is not a long-term monitoring satellite—its various instruments have expected lifetimes that range from approximately 14 months to 4 years.

[10] See app. B, "The Future of Remote Sensing Technology" in U.S. Congress, Office of Technology Assessment, *The Future of Remote Sensing From Space: Civilian Satellite Systems and Applications,* OTA-ISC-558 *(Washington DC:* U.S. Government Printing Office, July 1993).

[11] It is noteworthy, however, that changes to date in EOS program direction and funding have been initiated by the United States, not its international partners.

[12] NASA's description of the role of EOS in USGCRP appears in Ghassem Asar and David Jon Dokken, eds., *EOS Reference Handbook* (Washington, DC: NASA Earth Science Support Office), March 1993.

Box 3-A-Data Gaps in EOS

Specific needs to fill data gaps include:

- Launch of a stratosphericheposperic aerosol sensor to provides data continuity between SAGE II and EOS-AERO, scheduled for launch in the year 2000.[1]
- Launch by the mid-90s of a solar irradiance sensor to ensure overlap between ACRIM (currently flying on UARS) and EOS-CHEM, scheduled for launch in the year 2002.[2]
- Launch of an "ozone watch" sensor to provide continuity between UARS and EOS-CHEM of data necessary to assess and predict ozone depletion during the period of increasing stratospheric chlorine.
- Launch of an Earth radiation budget sensor to fillthe gap incritically needed observations of radiation and cloud forcing.[3]
- Launch of an ocean altimeter to provide measurements of ocean circulation between TOPEX/Poseidon and the EOS-ALT mission in 2002.
- Launch of a precipitation mapping sensor to provide data continuity after the TRMM mission in 1997.
- Launch of an ocean color measuring sensor to fill gaps that will develop when the SeaWIFS satellite fails (SeaWiFS is scheduled for launch in 1994).[4]

Specific flights required to fill ***measurement gaps*** include:

- Launch of sensors to measure changes in the Earth's magnetic field, and to provide better map of the geoid.
- Launch of global topographic mapping sensors to provide global high resolution digital topography in support of EOS objectives. Measurement of tropospheric aerosols will also be lacking unless a focussed monitoring program is initiated.[5]

1 Unless SAGE is flown on a small satellite or on what NASA terms a "flight (missJon) of opportunity." One such flight would be on a planned NOAA weather satellite that could accommodate SAGE without necessitating expensive modification of the bus or causing significant changes in the planned instrument package. NOAA's "AM" TIROS series Isa suitable candidate; a 1997 launch might be possible if funding is identified.

2 Unless the ACRIM mission is flown on a small satellite or on a mission Of opportunity.

3 Unless it is decided to rely in part on the European SCARAB radiation budget series, which will be initiated in 1993.

4 The likelihood of a follow-on to SeaWIFS would be increased if it is successful in demonstrating the commercial value of ocean color data.

5 For example on a small satellite such as "Climsat"—see box 3-F.

SOURCE: OTA Workshop and private discussions with EOS officials.

Workshop participants differed, however, in their views of the EOS instrument selection process. As noted earlier, some participants argued strongly that the program should have set its platform and instrument priorities after consultation with a broader group of Earth scientists than those selected by NASA.[13] EOS officials point to repeated and extensive reviews by interdisciplinary panels in the selection of instruments and instrument platforms as evidence that their program was appropriately reviewed. They also note that payload selection panels followed priorities set by members who were mostly scientists who would be the users of data, rather than instrument builders hoping for approval of a particular mission.

13 One workshop participant believed the conceptual changes that would normally accompany an evolving science program have been stifled because the intellectual underpinnings of EOS (and USGCRP) relied on the professional interest and time commitments of relatively few scientists and federal managers—a group small enough that a meaningful fraction were in attendance at the OTA workshop. Furthermore, this same group has been largely responsible for implementing EOS.

Several workshop participants and reviewers of this report who were familiar with the EOS review process objected to the close ties between NASA and its program reviewers.[14] In addition, several participants argued that EOS historical legacy (the system was first proposed as an adjunct to the Space Station—box 3-B) resulted in a flawed platform and instrument selection process. In particular, they argued that the selection process was not preceded by an appropriately rigorous identification of the outstanding questions for global change research and a subsequent matching of instruments and platforms to research questions. The result, according to critics, is an Earth observation program that relies too heavily on the use of relatively large and expensive satellites. Logically, the scientific component of the EOS program should be organized around a core set of fundamental questions generated by the collective wisdom of the best minds in the international Earth science community.

1 Reviewing Priorities

Reviews of the EOS program are complicated by the necessity to consider a myriad of technology issues, data management issues, and science issues. These issues are coupled among themselves and with the overarching problem of how best to structure the program given an uncertain funding profile.[15] Workshop participants were sharply divided on the question of whether the EOS program has an appropriate process in place to review priorities and undertake program corrections. Not surprisingly, disagreements were strongest between participants who believed the EOS program had missing elements or was misdirected, and those who felt the program's review process was already overburdened.

One participant, for example, argued that EOS would benefit from frequent institutionalized scientific reviews (e.g., every 6 months). This view was seconded by another participant who argued for a standing review committee, organized within the National Academy of Sciences and the National Academy of Engineering. Workshop participants agreed that the usual Academy study, which may take 18 months to complete, is too slow to be effective. In contrast, other participants expressed concerns that frequent reviews would delay programs and divert already stretched intellectual resources. Anecdotal evidence of this problem was provided by several participants; for example, one stated that work on EOS' data and information distribution system (EOSDIS) "essentially ground to halt" during the months that the National Academy was deliberating.[16] addition, OTA was told that work on EOS slowed while the EOS Engineering Review Committee (the ''Frieman Committee") studied the program in 1991.17

Some workshop participants also warned that the EOS program could not tolerate further changes in the near term. They argued that the two program restructurings left little flexibility in the payloads and that further changes would delay critical measurements (and possibly the entire program). These participants also noted that cuts in NASA's projected EOS budget had reduced the program to the point where additions of a new

14 For example, at least one participant believes the payload review panel (the Frieman committee) was strongly influenced by NASA Headquarters and project insiders in their deliberations. This participant questioned the independence of the committee, noting that some of the scientists on the Frieman panel were also members of particular instrument teams.

15 As noted above, NASA was instructed by Congress in the last round of budget cuts to plan to spend $8 billion on EOS during fiscal years 199 lto 2000. However, the $8 billion is a ceiling, not a floor. EOS budgets would appear to be particularly vulnerable to further budget cuts beginning in fiscal year 1995 when NASA plans to double the EOS budget to some $1 billion.

16 The NAS review of EOSDIS (the ''Zraket Committee' was chaired by Charles A. Zraket, former head of the MITRE Corp.

17 Program delays also occurred following the Frieman Committee as managers responded to recommendations by the Committee and to directions from Congress to reduce planned expenditures and adapt payloads from two large observatories to multiple smaller size satellites.

Box 3-B-Origins of the EOS Program

EOS is the principal element of NASA's Mission to Planet Earth (MTPE). The origins of MTPE and EOS can be traced to studies in the early 1960sthat considered the possibility of an international effort to study the Earth as a total system.1 The origins of MTPE were also influenced by two other developments occurring in this period: (1)the growth of the Space Station Program, (2)collaborations between NASA's Earth Sciences and Applications Division and the external scientific community that resulted in the formation of the Earth System Science Committee (ESSC) in 1963.

The ESSC, chaired by Franas Bretherton, produced a series of reports that focused on interactions of the traditional disciplines of the Earth sciences, rather than exclusively on the individual disciplines. ESSC'sactivities paralleled those being conducted by the National Academy of Sciences (NAS) in support of the 25th anniversary of the International Geophysical Year. This led to NAS proposals for comprehensive studies of the geosphere-biosphere. ESSC recommendations in 1966 for a unified study of global change were supported by NASA, NOAA, and the NSF. They were also supported by the influential NASA report, Leadership and America's ***Future in Space*** (the "Ride" report).[2]

Of particular interest for this background paper is the period in the mid-1980swhen NASA convened a group of Earth scientists to consider how they might use large human-tended satellites in low-Earth orbit. NASA planned to use the Space Shuttle, launched into polar orbit from the Western Test Range at Vandenberg Air Force Base, to maintain the satellites and change instruments. NASA offered to fund such a system of satellites-then known as System Z-out of the Space Station budget.[3] The System Z approach of using large polar platforms was also endorsed by the ESSC (which included several members of the System Z study). Part of the rationale for using large satellites was the potential to illuminate the interactions of earth processes by exploiting the capability of large satellites to carry several instruments that would acquire data on climate and other variables simultaneously.q

1 In 1982, NASA proposed a "Global Habitability" initiative at an international space conference called UNISPACE '82. However, the proposal received little support from the international community, in part because the conference became embroiled in the issue of the militarization of space. See US. Congress, Congressional Research Service, *Mission to Planet Earth and the U.S. Global Change Research program,* CRS 90-300 SPR, (Washington, DC), June 19, 1990. For a detailed discussion of the issues raised at UNISPACE '82, see US. Congress, Office of Technology Assessment, *UNISPACE '82A Context For International Cooperation and Competition,* OTA-TM-ISC-26 (Washington, DC U.S. Government Printing Office), March 1983.

2 Sally K. Ride, *Leadership and America's Future in Space: A Report to the Administrator,* (Washington, DC: U.S. National Aeronautics and Space Administration), August 1987.

3 According to officials at NASA and with the NAS, these proposals were made to increase the scientific rationale of the Space Station. See Gary Taubes, "Earth Scientists Look NASA's Gift Horse in the Mouth," *Science,* voi. 259, No. 5097, Feb. 12,1993, pp. 912-914.

4 Ibid.

instrument could occur only at the expense of one already planned.

However, as noted above, some participants believe the planned EOS is ill-suited for either long-term monitoring of key indices of global change or for mechanistic studies that might answer some of the key questions that underlie the agenda of the USGCRP. These participants believe that EOS would, in fact, benefit from a restructuring. Regardless of the scientific arguments, restructuring will be necessary if projected budgets for follow-ons to the first EOS "AM" mission do not materialize. Furthermore, tight budgets and renewed calls for a convergence of NASA, NOAA (National Oceanic Atmospheric Administration), and DOD

The connection with Space Station ended after the Challenger accident, when NASA terminated plans to launch the Space Shuttle into polar orbit. Nevertheless, the idea of using large polar platforms for studies of the Earth remained. The initial 1989 EOS proposal called for two 15-ton platforms, each carrying 12-15 instruments, which would be launched by a Titan IV rocket. NASA subsequently reduced EOS in cost and scope and distributed its instruments among a larger number of smaller (intermediate-class) satellites. These actions were taken in 1991 to respond to Congressional reductions in NASA's long-term budget projections (from $17 billion to 11 billion through FY 2000) and to ameliorate concerns about the consequences of a catastrophic failure of a *polar* orbiter.[5] Further cuts, which were part of a larger effort to control federal spending, later trimmed the decadal budget for EOS to $8 billion. This reduced program reserves and necessitated further reductions in planned science missions.

Critics of the current plan for EOS note that it evolved out of studies to match potential missions with the use of large satellites, rather than the more logical matching of scientific needs to a broad-based research program. Had EOS been designed initially to be an $8 billion program, it likely would be different than today's EOS program. NASA officials point to a series of planning meetings and program reviews which sought wide input from the scientific community as evidence that the program was organized correctly, regardless of its origins in the Space Station program.

[5] Such concerns are illustrated by the recent catastrophic tosses of the NOAA polar orbiter, NOAA-J, and Landsat-6.

(Department of Defense) remote sensing sensors and-satellites may also result in a restructuring of EOS. As part of its assessment on Earth Observation Systems, OTA is exploring the potential for such convergence. A report of its findings is scheduled for spring 1994.

EOS officials acknowledged that the history of the EOS program, which includes repeated changes to account for budget cutbacks, has resulted in a program that may be less optimal than one that began from scratch. However, they believe the current program is sufficiently close to the ''right program that further modtifications would do more harm than good. In particular, they note that program restructuring would lead to delays and added costs, which might require further program rescoping.[18] Critics of this view note the long-term horizon of global change research. They argue that a program designed to last for decades will only be successful if mechanisms are in place to facilitate mid-course corrections in mission planning that account for shifting scientific priorities, changes in technology, and scientific surprises.

IS THE PROGRAM SCIENTIFICALLY SOUND?

Most OTA workshop participants agreed that research programs organized to address the outstanding scientific questions related to global change are a prerequisite for informed policymaking. However, as in the debate about whether to limit chlorofluorocarbon emissions to protect the ozone layer, policymakers will inevitably be forced to make decisions that will affect the global environment without the benefit of complete knowledge. Nevertheless, the "right' EOS and USGCRP program can bound uncertainty and thus illuminate the risks and benefits of alternative decisions.[19]

18 one workshop participant made a similar comment when asked about the effect of further budget cuts on EOS: ' 'There is a strong axiom in satellite programs that if you want to do the job for a lower sum of money, you go through a design process; you make a commitment, and then you finish it as fast as you possibly can. '

19 As one participant explained, "It is rational to proceed despite scientific uncertainties . . . provided that the actions are modest enough to fail gracefully and to discover what works through trial and error in the field. "

Some critics of the EOS program argue that the program should be focused on specific problems chosen to elucidate key areas of scientific uncertainty.[20] This view coincides with the charge that the EOS (and USGCRP) programs are operating without a ''scientific foundation, ' which would link key global change questions through a network of detailed questions to a responsive course of action (box l-A). A key objective of global change research is to achieve a level of understanding of Earth processes that would be adequate to predict future climate behavior. Several workshop participants believe this will not be possible without a different EOS program--one that would have greater emphasis on studies of processes to facilitate establishment of cause and effect.

EOS officials respond to these criticisms in several ways. First, they defend their decision to have a broad-based program as a prudent strategy to respond to scientific surprise.[21] Second, they note that program reviews have been performed by panels assembled by the National Academy of Sciences. Finally, while admitting that the list of EOS priorities is superficial from a scietific standpoint, officials note that embedded in these priorities is a detailed list of scientific questions not too different from those the critics charge is missing.

These responses did not satisfy workshop participants who cited examples of missing program elements—for example, unpiloted air vehicles to perform detailed process studies (box 3-C)--and missing instruments-for example, monitoring of solar irradiance-as evidence that the program could be strengthened scientifically. Some participants question the adequacy of EOS to answer even those scientific questions that are currently recognized.

Participants also debated whether EOS was appropriate for monitoring long-term (decade to century) climate changes. Skeptics cited several reasons to question the utility of EOS for monitoring. For example, one participant stated that: 1) the EOS measurements will not include all the major forcings and feedbacks (box 3-D)[22], 2) the EOS system will not have ready-to-launch spares and the instrument calibration plan does not include transfer of calibrations among satellites in the series, and 3) the very high cost of EOS does not make it practical to maintain the system for very long time periods. These concerns overlap other issues discussed in this chapter.

I The Role of EOS in Earth Monitoring and Process Studies

The range of Earth remote sensing research objectives can be divided into two broad categories:

1. Long-term monitoring: to determine how climate is changing, to distinguish human-induced from naturally-induced climate change (and its impacts), and to determine global radiative forcings and feedbacks.
2. Mechanistic or process studies: detailed analysis of the physical, chemical, and biological processes that govern phenomena ranging from the formation of the Antarctic ozone hole to the gradual migration of tree species.

Although these two categories cannot be clearly delineated, a process study usually extends over

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20 According t. James G. Anderson, ''The idea that gathering data is equivalent to solving problems is a fallacy. You can collect huge amounts of data, but if those are not carefully matched to problems, then the data just gather in databanks and you make no progress. ' See "Earth Scientists Look NASA's Gift Horse in the Mouth,'' op. cit., footnote 6.

21 For example, former EOS project scientist, Jeffrey Dozier explains, ''What we haven't done [in planning EOS] is ask a question and design an instrument to answer that question, What we have instead tried to do is design instruments with a range of measurement capabilities so they can answer a lot of questions, some of which we haven't been smart enough to ask yet. ' Dozier quoted in Science, ibid.

22 This participant suggested that the large size, high spatial resolution, and poor time sampling of EOS satellites would make them better suited for measurement of land-use, biodiversity changes, and the effects of changing population.

Box 3-C-Unpiloted Air Vehicles

Unpiloted air vehicles (UAVS) are particularly suited for making measurements at or near the tropopause, where the qualify of remotely sensed data from both ground- and space-based platforms is poor. If developed, along-endurance (multiple diurnal cycles) high-altitude UAV would become effectively a geostationary satellite at t he tropopause. The tropopause is of particular interest because it marks the vertical limit of most clouds and storms.[1]

Researchers interested in elucidating mechanisms for ozone depletion are partiwlariy interested in obtaining a stable, controllable, long-endurance platform that could be instrumented to monitor conditions in the stratosphere at altitudes up to and above 25 km (approximately 82,000 feet). Scientific explorations of this region are currently hampered by the uncontrollability of balloons, the inadequate altitude capabilities and high operating costs of piloted aircraft, and the inadequate measurement capabilities of most satellite instruments for the lower stratosphere. Instruments on UAVs could be changed or adjusted after each flight. UAVS, therefore, are potentially more responsive to new directions in research or to scientific surprises than are satellite systems. UAVS have also been proposed as platforms for releasing instrument packages from high altitudes, which can provide targeted measurements of climate and chemistry variables at different altitudes in the atmosphere.

High-altitude UAVS have a smaller payload capability than currently available piloted aircraft. However, they have several advantages that make them particularly attractive for climate research:

- UAVS under design should reach higher altitudes than existing piloted aircrafi. For example, NASA's piloted ER-2 can reach the ozone layer at the poles, but it cannot reach the higher altitude ozone layer in the mid-latitude and equatorial regions that would be accessible to a UAV.
- UAVS can be designed to have longer endurance than piloted aircraft.
- UAVS should have much lower operating costs than piloted aircraft.[2] (UAV studies predict savings of an order of magnitude or more.) Researchers hope the relatively low cost of UAVS compared with piloted aircraft would translate into more research aircraft and greater availability of aircraft.
- UAVS do not have the flight restrictions of piloted aircraft. For example, for pilot safet y reasons, the ER-2 is restricted to daytime fright. UAVS also alleviate concerns about pilot safety on flights through polar or ocean regions.
- UAVS would be designed to fly at high altitudes at subsonic speeds. Supersonic high altitude aircraft like the SR-71 (cruise altitude over 80,000 feet) are not suitable for many in-stu experiments because they disturb the atmosphere they are sampling {e.g., the chemical species involved in ozone depletion).

Both NASA and the Department of Energy plan to use UAVS for key experiments. in addition, the development of sensors for UAVS relates closely to the development of sensors appropriate for smallsatellites.

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1 In the tropics, the tropopause can reach altitudes of 18 km. Monitoring the tropopause with airborne platforms therefore requires vehicles capable of reaching an altitude of some 20 km. NASA's piloted ER-2 can reach this altitude, but it is restricted to frights of 6 hours. A iong duratio UAV flying at or below the tropopause would facilitate measurements necessary for global circulation models of the Earth's atmosphere and climate. These measurements would complement those being made by DOE as part of its ground-based Atmospheric Radiation Measurement Program (ARM), whose objectives are to improve models of the Earth's climate with regard to: 1) radiative energy balances, and 2) aloud formation, maintenance, and dissipation,

2 For example, direct and indirect costs to operate the ER-2 total to some $9,900/hour when calculated for a typical year of approximately 1,000 hours of flight operation. NASA considers direct costs as those associated with actually flying an aircraft and paying for support personnel. For the ER-2, these total to some $2,900/hour. This figure neglects indirect costs such as spare parts, maintenance and shipments (via cargo aircraft) to remote staging areas.

3 in their Atmospheric Radiation Measurement program.

(Continued on next page)

Box 3-C-Unpiloted Air Vehicles-Continued

Despite the potential of UAVs to enable measurements that are crucial o rglobal change research, congressional support for civillan[4] UAV development, and associated instrumentation, has been meager and maybe inadequate to provide a robust UAV capability.

EOS officials acknowledge the utility of both UAVS and small satellites (see box 3-D) in fashioning a more balanced program of Earth observations. In fact, the administration's Committee on Earth and Environmental Sciences proposed amid-course correction to the fiscal year(H) 1993 budget request that would have added money for small satellite and unmanned aircraft programs. However, these funding increments were not approved by Congress.[5]

NASA's previously tepid support for UAVS changed in 1993 when NASA Administrator Daniel Goldin proposed a large increase in the agency's UAV budget (to some $90 million over 5 years). NASA's EOS budget for FY 1993 is scheduled to double by FY 1995. Whether it will be possible to achieve this budget growth and increase funding for new starts such as UAVS remains an outstanding issue. However, several workshop participants noted that a program that cannot fund what maybe among its most cost effective science missions would appear to be in need of redirection.

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4 A variety of military UAV programs exist, some of which might be adaptable for global change research. For example, a long-endurance, solar-powered, eight-motor unpiloted flying wing that would carry lightweight interceptor missiles (dubbed Raptor/Pathfinder) is under development for applications in ballistic missile defense. However, the only military UAV that would be available in the near term for global change research would be the Boeing Condor, a large and heavy (200 foot wingspan, 20,000 pound) propeller-driven UAV that holds the altitude record for a propeller driven aircraft (67,026 feet or 20.4 km), The Condor has the range and payload capability to be useful to atmosphere scientists; furthermore, proposals existtoextend its operating ceiling to even higher altitudes. Condor would be an expensive vehicle to buy and adapt for scientific research. Even a low estimate of the oost required to restore one Condor for use in atmosphere research is some $20 million; yearly maintenance costs have been estimated at several million dollars or more.

5 AS one workshop participant, frustrated by the process that orders and funds priorities for EOS and USGCRP, explained:

> . . . aft of us within CEES (Committee on Earth and Environmental Sciences) [recognized] that the role of unmanned aircraft was important; the role of small satellites was important . . . [when] restarted to sell this program ten years agoorsixyearsago there should have been an unmanned aircraft component. *What we should have done, though, was have a generic correlative measurement component that would have then been able to adapt to a new, changing environment when new technologies came onboard.* [emphasis added]

a shorter period than a monitoring study. Process studies are typically designed to elucidate the details of a particular mechanism of some geophysical, chemical, or biological interaction. The distinction between process studies and long-term monitoring studies is least useful for studies of the land surface, which may require years or data acquisition. For example, studies of terrestrial ecosystems may require decades of calibrated observation.

OTA asked workshop participants to evaluate the utility of EOS and satellite alternatives for both long-term monitoring studies and for detailed process studies. The concluding sections of this chapter summarize some of their observations.

Monitoring STUDIES

The satellite portion of an environmental monitoring system should be designed to make continuous, long-term (decades to centuries), calibrated measurements of a carefully selected set of climatological and other variables. For most monitoring programs, global coverage will be required. In addition, measurement frequency and instrument spatial resolution must be matched to

Box 3-D–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. 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 by the burning of fossil fuels. The distinction between forcings and feedbacks is sometimes arbitrary; however, forcings are quantities normally specified in global climate model simulations, for example, CO_2 amount, while feedbacks are calculated quantities. Examples of radiative forcings are greenhouse gases (CO_2, CH_4, CFCS, N_2O, OS, stratospheric H_2O), aerosols in the troposphere and stratosphere, solar irradiance, and surface reflectivity. Radiative feedbacks include clouds, water vapor in the troposphere, sea-ice cover, and snow cover. For example, an increase in the amount of water vapor increases the atmosphere's absorption of long-wave radiation, thereby contributing to a warming of the atmosphere. Warming, in turn, may result in increased evaporation leading to further increases in water vapor concentrations.

The effects of some forcings and feedbacks on climate are both complex and uncertain. For example, clouds trap outgoing, cooling, Iongwave infrared radiation and thus provide a warming influence.[1] However, they also reflect incoming solar radiation and thus provide a cooling influence. Current measurements indicate t hat the net effect of clouds is to cool the Earth. However, scientists are unsure if the balance will shift in the future as the atmosphere and cloud formation, maintenance, and dissipation are altered by the accumulation of greenhouse gases. Similarly, the vertical distribution of ozone (O_3) affects both the amount of radiation reaching the Earth's surface and the amount of reradiated infrared radiation that is trapped by the greenhouse effect. These two mechanisms affect the Earth's temperature in opposite directions. Predicting the climate forcing resulting from ozone change is difficult because the relative importance of these two competing mechanisms also depend on the altitude of the ozone change.

[1] For a more detailed discussion of these subjects see V. Ramanathan, Bruce R. BarkStrom, and Edwin Harrison, "Climate and the Earth's Radiation Budget," Physics Today, vol. 42, No, 5, May 1989, pp. 22-32. Also see J. Hansen, W. Rossow, and 1. Fung, "Long-Term Monitoring of Global Climate Forcings and Feedbacks," Proceedings of a Workshop heid at NASA Goddard Institute for Space Studies, Feb. 3-4, 1992.

SOURCE: Office of Technology Assessment, 1993.

the phenomena under study, The decades of measurements required by many monitoring programs exceed the lifetime of any single satellite; therefore, monitoring programs will require satellites to be flown repetitively. To distinguish subtle trends, a new satellite should be launched while its predecessor is still functioning. Furthermore, technical innovation in sensor or satellite design should be a lower priority than ensuring the stability of data and data analysis algorithms, In contrast, research flights for process studies require maximum flexibility. These two extremes—process-oriented studies and long-term monitoring are part of EOS' plan. However, a single system may not be appropriate for both types of measurements.

EOS instruments will acquire data on climate processes; however, study of climate *change* requires measurements over decades with full continuity and calibration of instrurnentation. In addition, the comparatively large, expensive, and high data-rate system of EOS is, according to one panelist, "fundamentally unsuited for long-term precision monitoring of global climate forcings. For example, sampling of diurnal variations will be limited because the high cost of EOS satellites prohibits flying two spacecraft in different orbits at the same time. Flying less expensive satellites would facilitate overlapping operations of satellites, which is necessary to transfer calibrations between instruments orbited sequentially as part of a decadal monitoring effort. Finally, the constrained fiscal environment of the foreseeable future makes it unlikely that an EOS level of effort and expenditure could be sustained for decades. Indeed, as noted above, further budget cuts could prevent the completion of even the planned 15 years of operations.[23]

Some panel members believe EOS should be augmented with small satellite systems specifically designed for long-term monitoring (box 3-E). The NASA Goddard Institute for Space Studies "Climsat" proposal is an example of such a system (box 3-F).[24] If successful, Climsat satellites would carry out a core group of key remote sensing measurements for many decades. Supporters of Climsat believe that the data that would be gathered by Climsat, or a similar system, are 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 further expense of an already diminished EOS program. Noting that Climsat addresses only a narrow part of the climate problem, some critics also question whether data from Climsat are, in fact, more important than other data, including ocean color, land-surface productivity, atmospheric temperature and humidity, and snow and ice volume.

EOS officials acknowledge that the program is not designed for long-term monitoring. However, they argue that EOS will acquire 15 years of high-quality time-series of data that can be extended to the future as EOS research instruments are incorporated on operational satellites, such as the NOAA weather satellites. For example, eventually NOAA might fly a version of the high-resolution atmospheric' infrared sounder (AIRS), scheduled for inclusion on EOS PM-1, on its operational satellites.

MECHANISTIC OR PROCESS STUDIES

Satellites play a central role in global change research because they facilitate global, synoptic, and repeatable measurements of many Earth systems. For economic reasons, surface-based measurements cannot provide similar coverage. In addition, regular monitoring of remote parts of the globe is impractical using surface-based instruments.

Satellite sensors may be employed to monitor changes in global biomass, land use patterns, and in the oceans and remote continental regions. They can also be used for direct measurement of the regional to global scale phenomena that are the main components of the climate system. However, satellite-based measurements also have a number of limitations that restrict their utility for certain process studies.[25] These include limited spatial and temporal resolution, and an inability to sample the atmosphere (or surface) directly. Furthermore, optimizing a satellite-based sensor to improve one of these characteristics frequently requires sacrifice of the other.[26]

While satellites can examine regional interactions, balloon and aircraft-based instruments can be targeted directly on the smaller scale aspects of climate processes. Such instruments can also be

23 Evidence of this concern appeared in the debate over whether EOS "PM-1" should have been launched before "AM-l. " Concerned that "worst-case" budget cuts might force program termination after a single launch, some scientists argued for launching PM's high-priority climate measuring instruments before AM. Further evidence is seen in ongoing discussions of possible downsizing of the PM platform and possible convergence of parts of EOS with NOAA and DOD programs.

24 Box 3-F discusses the Climsat proposal to illustrate the utility of using small satellites for long-term monitoring. Competing and alternative proposals to Climsat exist; however, these were not discussed at the OTA workshop,

25 For example, satellite-borne sensors are unable to measure climatological variables to the precision necessary fOr certain numerical weather and climate models, and their ability to determine temperature, moisture, and winds is inadequate for meteorologists interested in predicting, rather than just detecting, the formation of severe storms and hurricanes.

26 For example, a satellite in low-Earth orbit wilt have a revisit time cf several days to approximately two weeks, depending on its capability to gather data from areas that are not directly below its path. High time resolution can be obtained from geo-stationary orbits (because the Earth appears motionless with respect to the satellite), but then spatial resolution and coverage are sacrificed. The high altitude of gee-stationary orbit affords a broad, but fixed and limited (e.g., no polar data), view of the Earth.

Box 3-E-Small Satellites

Small satellites have been defined as costing $100 million or less including spacecraft, instruments, launch, and operations. Workshop participants generally agreed that the EOS program should make greater use of instruments based on small satellites as a way to fill gaps between existing and planned satellites and to augment or complement data that will be acquired by larger satellites. For example, NASA's existing Earth Probes series of satellites could be augmented with a new Earth Explorer Mission series. However, such an expansion would likely require supplemental funding if NASA *were* to avoid restructuring EOS programs already approved by Congress.

Small satellites have three advantages compared to larger systems. First they are characterized by relatively low cost compared to larger satellites.[1] This encourages technical innovation, which might otherwise be judged too risky. Small satellite proponents see this advantage as the key to enabling rapid, affordable augmentation and modernization of larger satellites. Second, a variety of defense and civil small satellite programs have already demonstrated that instruments, spacecraft, and launch of small environmental satellites would be possible in a program of only a few years or less, Typically, development of a small satellite avoids the potential problems associated with managing the integration of multiple instruments on a single platform. Shortening the time to launch would also 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 experimenters to optimize satellite orbits for a particular set of measurements.[2]

NASA, DOE and ARPA (Advanced Research Projects Agency) are examining small satellite systems for three roles in the U.S. Global Change Research Program+ 1) to address gaps in long-term monitoring needs prior to the launch of EOS satellites, 2) to provide essential information to support process studies prior to, and complementary with, the restructured EOS, and 3) to allow for innovative experiments to demonstrate techniques that greatly improve the ability to monitor key variables or improve/speed up the process studies

1 They also weigh less and can use less costly launchers. However, launchers are not the real cost drivers in the EOS program. Multi-instrument EOS AM and PM satellites and proposed EOS facility instruments—LAWS, SAR, and HIRIS—require a launcher in the Attas 2AS-class. Launch costs with an Atlas 2AS may be some $130 million, but this is 20 percent or less of total system costs (which also includes ground segment costs).

2 However, some missions require nearly simultaneous measurements by instruments that cannot be packaged on a single satellite. In this case, a larger platform carrying several instruments maybe desirable. Another option would be to attempt to fly small satellites in dose formation.

3 See Committee on Earth and Environmental Sciences (CEES) of the Federal Coordinating Council for Science, Engineering, and Technology, *Report of the Small Climate Satellites Workshop,* (Washington, D.C.: Office of Science and Technology Policy, May 1992).

4 Ibid., pp. 20-21,

SOURCE: Office of Technology Assessment, 1993.

altered more frequently to respond to new research directions, whereas the development cycle for satellite instruments makes them more suited for longer term observation programs,

Aircraft studies of the physical and photochemical processes responsible for the formation and persistence of the Antarctic ozone hole provide an illustrative example of the kind of measurements that cannot be made from space. NASA-sponsored aircraft experiments in the winter of 1992 found very large discrepancies with conventional explanations of the mechanisms responsi-

Box 3-F-CLIMSAT

Climsat is a proposed system of two small satellites,[1] each carrying three in stmments, that would monitorthe Earth's spectra of reflected solar radiation and emitted thermal radiation. Climsat satellites would be designed to be self-calibrating, small enough to be orbited with a Pegasus-class launcher[2] long-lived (nominally 10 years or more), and relatively inexpensive.[3] Proponents believe Climsat 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. In principle, it would be possible to continue the Climsat measurements for decades beyond the scheduled end of the EOS program.

Climsat alone could not fulfill the broader objectives of the Mission to Planet Earth and the Earth Observing System Programs. Proponents of Climsat envision combining Climsat observations, planned EOS observations, and ground-based measurements of temperatures, winds, humidities, aerosols, and vertical ozone. Supporters of Climsat also believe ACRIM, an instrument to monitor solar output, should be part of a long-term program to monitor global change.[4]

Both the baseline EOS program and the baseline Climsat proposal have been revised since their initial presentations. Versions of two of the three Climsat instruments are nowscheduledfor later EOSflights. 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!
- Allow instrument modification on a shorter time-scale than EOS instruments and thus be better able to respond to scientific surrprises. Supporters also argue that Climsat instruments are better designed to handle scientific surprises because:
  1. Unlike related larger instruments on EOS, they cover practically the entire reflected solar and emitted thermal spectra.
  2. The Climsat instruments measure the polarization as well as the mean intensity of the solar Spectrum.[e]

1 AS described below, the baseline Climsat proposal specifies this number because it is necessary and sufficient for global coverage and for adequate sampling of diurnal variations.

2 A launch on Pegasus costs about $10-12 million. Pegasus can carry payback weighing Up to 900 pounds.

3 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 to 20 million for first copy.

4 The primary objective of ACRIM Is to monitor the variability of total solar Irradiance with state-of-the-art accuracy and precision, thereby extending the high-precision database complied by NASA since 1980, Maintaining a continuous record of solar irradiance and launching sensors frequently enough to have overlapping operation (to transfer calibration) is necessary to distinguish subtle variations in solar output. However, the only ACRIM sensor now in orbit is on UARS, a satellite whose useful lifetime is expected to end in 1994. NASAplans to launch ACRIM as part of the EOS-CHEM payload, but EOS-CHEM is not scheduled for launch until the third quarter of 2002. if funds can be identified, EOS program officials hope to launch ACRIM earlier on a "flight of opportunity." Climsat supporters would fly ACRIM as soon as possible on a separate small satellite.

5 According to Dr. James Hansen, developer of the Climsat proposal, the Climsat satellite would require three years to build and launch after approval and procurement processe8 were complete.

6 polarization refers to the directional dependence of the electrical field vector Of electromagnetic radiation. Analysis of the polarization of reflected light oan provide unique Information about scene characteristics. it can also determine aerosol characteristics. See discussion of Climsat and EOSP in app. B of *The Future of Remote Sensing from Space: Civilian Satellite Systems and Applications*, ORA-ISC-558 (Washington, DC: US. Government Printing Office, Jufy 1993).

ble for ozone depletion.[27] This result was very surprising; moreover, explanations for the discrepancies showed that simultaneous high-resolution observations (on the scale of 0.1 kilometer in vertical extent) of the concentration of multiple chemical species were necessary to diagnose the operative mechanisms properly.

EOS AND BALANCE WITHIN THE USGCRP

OTA workshop participants generally agreed that the USGCRP would benefit from a more balanced program between satellite and other types of studies. Forexample, participants strongly urged greater support for correlative (''ground-truth' measurements that would support and complement satellite measurements. As noted above, many also urged greater support for process-oriented studies to facilitate establishment of the physical and chemical mechanisms responsible for global change. The need for a long-term monitoring system has also been noted in this paper.

Several workshop participants attributed deficiencies in the USGCRP to the failure of agencies charged with nonsatellite research to acquire resources necessary to fulfill roles anticipated in the original formulation of the Program. Attempting to redress this problem either through redirection of NASA funds, or through funding increments, raises several policy issues whose resolution is beyond the scope of this background paper. They include:

- Should NASA be the lead agency for both space and non-space based measurements?
- If not, will agencies other than NASA embrace USGCRP as a priority and give nonsatellite programs sufficient attention and funding?
- Is NASA, which has traditionally been responsible for research and development of space technology, the appropriate agency to be charged with long-term environmental monitoring?
- Is it realistic to expect Congress to appropriate large percentage increases in agency global change budgets? If not, does NASA become the de facto lead agency for both space-based and non space-based programs? What consequences might arise from NASA assuming these roles?
- Would requiring agencies to "fence off' their contributions to the USGCRP result in greater support for non-satellite programs?

[27] Analysis of in-situ measurements of chlorine monoxide at mid- and high northern latitudes during the period October 1991 to February 1992 indicates that chlorine species play a greater role, and oxides of nitrogen a lesser role, than previously thought in the catalytic destruction of ozone in the lower stratosphere. See D.W. Toohey et. al., "The Seasonal Evolution of Reactive Chlorine in the Northern Hemisphere, " *Science*, vol. 261, No. 5125, Aug. 27, 1993, pp. 1134-1135.