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Committee on Science, Space, and Technology
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Chairwoman Horn, Ranking Minority member, and members of the Committee, I want to thank you for the opportunity to testify today at the hearing on “Discovery on the Frontiers of Space: Exploring NASA’s Science Mission.” My name is Chelle Gentemann and I am a Senior Scientist at Earth and Space Research, a nonprofit research institute located in Seattle, Washington, an Affiliate at the University of Washington Applied Physics Laboratory, Co-Chair of the National Academies of Sciences, Engineering, and Medicine (NASEM) Standing Committee on Earth Science and Applications from Space (CESAS), and acting Chair of NOAA’s Science Advisory Board’s Data Archive and Access Requirements Working Group. I live in Santa Rosa, California, which you may recall was devastated in 2017 by wildfires.

I am a remote sensing physical oceanographer specializing in measuring ocean temperature from space and using those observations to advance our understanding of the upper ocean and how ocean variability imprints onto atmospheric weather. I’ve led several large commercial, governmental, and academic scientific coalitions funded by the National Oceanographic Partnership Program, NASA, NOAA, and the Office for Naval Research. This includes leading U.S. participation in an international science team organized to advance utilization of satellite observations.

Although parts of my testimony follow the specific recommendations and supporting text in the 2017-2027 Decadal Survey for Earth Science and Applications from Space (ESAS; “Decadal Survey”), the opinions I express should be attributed to me unless stated otherwise. I will provide thoughts on the scientific aspects of the Science Mission Directorate (SMD) portfolio to the subcommittee below.

Earth science and derived Earth information have become an integral component of our daily lives, our business successes, and society's capacity to thrive. The Decadal Survey and the popular version of that report that we've provided at this hearing[1] enumerate, in much greater detail than I can provide here, the benefits to the nation from a robust earth science program at NASA, as well as the earth observation programs at NOAA and the US Geological Survey.

Some 100 of the nation's leading earth scientists, space system engineers, and policy experts worked over nearly two years in developing the community consensus on earth science priorities that informs the Decadal Survey's recommendations for U.S. investments in support of earth science from space. The Decadal Survey builds on, and has as its highest priority, the completion of the Program of Record (POR). The POR includes both PACE and CLARREO Pathfinder (see more details below). Elimination of these missions in the POR undermines the entire Decadal Survey planning and prioritization process. PACE in particular supports multiple research thrusts and is a key element in the survey's planned constellation of earth observation satellites that will give scientists and policymakers a clearer understanding that will help prioritize climate change mitigation options and strategies. CLARREO Pathfinder will provide the ability to inter-calibrate instruments in space at accuracies 5 to 10 times beyond current capabilities. As you consider NASA's reauthorization, I hope that the committee sees the value of the Decadal Survey process and enables NASA to continue its implementation for all our benefit.

Finally, I note that rapid advancements in using commercial cloud computing and open source software for science have outpaced planned activities. I believe there are public-private partnership opportunities in cloud computing and open source software that could lead to breakthrough science and new commercial applications.

What are some of the most compelling scientific questions and opportunities in earth science and applications today?

The most recent National Academies' "Decadal Survey" for Earth Science and Applications from Space (ESAS), produced the report, Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space. A summary of this community report is appended to my testimony. The report begins by noting that understanding our planet, and how it is changing, is critical for our nation's economy, security, and safety. As individuals, we rely on Earth information in our daily lives for applications ranging from internet mapping and weather forecasting to agricultural

[1] both online at: https://www.nap.edu/catalog/25437

productivity and transportation. These ever-growing capabilities are due in large part to the United States' sustained commitment to satellite-based earth observations.

Satellite observations provide a global perspective of Earth that transforms our scientific understanding of the planet and enables powerful societal applications that help individuals, businesses, the nation, and the world. *The report identifies and prioritizes the science and applications and observations that are needed to understand the dynamic Earth over the next decade.* Pursuing these identified priorities will impact all our lives.

A major component of the Decadal Survey's recommendations included a commitment to a set of observational capabilities to enable substantial progress in all of the following science and applications areas:

- Providing critical information on the make-up and distribution of aerosols and clouds, which in turn improve predictions of future climate conditions and help us assess the impacts of aerosols on human health;
- Addressing key questions about how changing cloud cover and precipitation will affect climate, weather, and Earth's energy balance in the future, advancing understanding of the movement of air and energy in the atmosphere and its impact on weather, precipitation, and severe storms;
- Determining the extent to which the shrinking of glaciers and ice sheets, and their contributions to sea-level rise, is accelerating, decelerating, or remaining unchanged;
- Quantifying trends in water stored on land (e.g., in aquifers) and the implications for issues such as water availability for human consumption and irrigation;
- Understanding alterations to surface characteristics and landscapes (e.g., snow cover, snow melt, landslides, earthquakes, eruptions, urbanization, land-cover and land use) and the implications for applications such as risk management and resource management;
- Assessing the evolving characteristics and health of terrestrial vegetation and aquatic ecosystems, which is important for understanding key consequences such as crop yields, carbon uptake, and biodiversity; and
- Examining movement of land and ice surfaces to determine, in the case of ice, the likelihood of rapid ice loss and significantly accelerated rates of sea-level rise, and in the case of land, changes in strain rates that impact and provide critical insights into earthquakes, volcanic eruptions, landslides, and tectonic plate deformation.

Key issues for Congress regarding the future of space and earth science.

The overarching challenge continues to be how to sustain the baseline and implement the new, critical programs at NASA, NOAA and USGS that are recommended in the Decadal Survey. This will require a combination of continued and perhaps expanded levels of Congressional support, leveraging the emerging opportunities associated with "new space," the commercial sector, and building on the revolution in how data are accessed, managed, and analyzed.

Finally, and most importantly, climate change poses enormous challenges to our way of life and security. The role of earth observations in understanding where and how fast changes will occur, along with informing options for mitigation and adaptation, must be a key element of all observational programs.

What may impact addressing the most compelling scientific questions and opportunities?

Endangered POR components:

PACE mission. PACE (Plankton, Aerosols, Cloud, ocean Ecosystem) is a critical mission for quantifying the role of the ocean ecosystem in the global carbon cycle. When launched, it will give us unprecedented insight into Earth's ocean and atmosphere. Collecting data on these systems is critical to understanding their effects on climate and Earth's habitability. The instruments on PACE will allow for a more detailed understanding of the carbon uptake by the various phytoplankton species. This data will allow scientists and policymakers a stronger position when prioritizing climate change mitigation strategies.

CLARREO-Pathfinder mission. CLARREO-Pathfinder (CPF) is designed to demonstrate in space satellite inter-calibration, traceable to the International Standard of Units. Instrument calibration is essential to providing accurate, well-characterized data. Currently, after launch, instrument scientists often rely on overlapping periods of data from similar sensors, models, evaluating data with collocated in situ observations (when possible), or other suboptimal methods to calibrate satellite instruments. CPF will provide the ability to inter-calibrate instruments in space at accuracies 5 to 10 times beyond current capabilities, allowing them to be combined into accurate data products for weather forecasting and climate modeling. CPF is part of the survey's assumed baseline program of record.

Endangered technological advancements

Continue STEM education. Although one of the richest countries in the world, the U.S. scores in STEM are consistently below average among similar countries. Within the digital world, national borders mostly disappear, and without a competitive and educated workforce the next 'Silicon Valley' could be overseas. Remaining the global leader in technology requires training students in advanced STEM skills.

Enabling Breakthrough Science

The Decadal Survey report stated "Breakthrough science will be done by virtual science teams collaborating through complex, multi-observation data sets," but didn't go farther to explore this as it was determined to be beyond scope. Right now, we are witnessing the rapid, revolutionary transition into a new era in science. Open-source software, cloud data storage, and cloud computing have the potential to enable more widespread and efficient utilization of public data for a myriad of commercial and scientific applications, and new approaches to understanding complex interconnections between our economy, ecosystem, weather, and environment.

The Decadal Survey authors didn't plan for the additional resources needed for a wholesale move of NASA data assets onto the cloud, support for the open source software libraries that underpin rapid scientific advancements and commercial data applications, or how to enable the interdisciplinary science and commercial applications that will subsequently flourish. In my view, this is one example where comparatively small new investments have the potential to deliver outsized benefits. NASA's vast data resources and robust research community make it well-poised to be a global leader in this effort. Jump-starting these activities in NASA could grow the private-public cloud partnership and energize the research community.

There are a couple studies that would help cloud-migration efforts. NASA's data is more than just the observation value, there is also metadata (data about the data) and uncertainty estimates. There are many different approaches to estimate the uncertainty in a measurement, from using artificial intelligence to a careful detailed analysis of how each step contributes to uncertainty. As data moves onto the cloud, the calculation of uncertainty and how it is communicated becomes even more important.

The organization of Federal agencies and funding opportunities directly impact how science is accomplished and can act as either a barrier or enabler for new approaches. A movement of data onto the cloud can easily propagate a 'business as usual' approach to science, but early adopters have found that by removing many of the barriers to data access, how science is accomplished is changing. It changes the type of questions that can be asked, how they are answered, the reproducibility of science, and the dynamic of collaborations. This enables more interdisciplinary research. Capturing all the advantages of cloud computing and open source software will require a re-imagining of how science is organized.

How does CESAS monitor the implementation of the Earth Science Decadal Survey, and what is CESAS's assessment of NASA's progress in implementing the decadal to date?

At twice yearly meetings, NASA is invited to present on their progress and decisions regarding the implementation of the Decadal Survey recommendations.

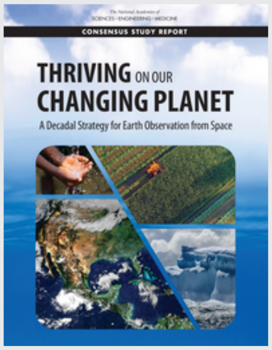
During these presentations, and afterward, there is substantial back-and-forth with CESAS. Afterward, the committee may submit a report to NASA outlining any areas of concern or ask for additional meetings to address specific questions.

NASA is following the Decadal Survey guidance and has as its first priority the completion of the POR. It has also started studies on the implementation of all the recommended "Designated Observables," a program element for Decadal Survey-designated cost-capped medium- and large-size missions to address observables that are *essential* to the program, directed or competed at the discretion of NASA. However, it now appears that implementation of the rest of the recommended program will require appropriations beyond that assumed by the Decadal Survey committee. In particular, additional funds would be needed to initiate the Earth System Explorer line, a new program element involving competitive opportunities for cost-capped medium-size instruments and missions serving specified Decadal Survey-priority observations.

How, if at all, do emerging capabilities in the commercial sector affect the future of earth science and applications?

NASA has contracts with three private companies (Planet, DigitalGlobe, Spire) to buy existing data related to climate variables. These are being evaluated by a broad set of NASA researchers to determine the value of the geophysical information for advancing NASA research and application objectives. These scientists are exploring uses for this data. If these commercial data providers are able to demonstrate products that add value to research and are cost-effective, it will make sense to continue buying and using their data. Yet, in the scientific community, a high level of concern persists about the potential impacts of long term reliance on commercial space companies and loss or internal expertise. At the same time, it is apparent that commercial partners may be more agile and experimental, which impacts possible solutions, cost, and risk.

Emerging capabilities hold promise, but there must be a close collaboration. It is important to consider in detail the design of the data-producing instrument when evaluating data quality. Maximizing data utilization requires close collaboration between data users and data providers, which should begin well before the point when flight data are actually available. Ideally, the engineering process should include the involvement of potential users in the design, development and pre-flight calibration of an instrument. At an absolute minimum, the data users should have access to the detailed engineering design and test results for instruments that measure the data they are buying. This runs into issues of company equipment and security and has the potential to weaken the strength of the average datum used in scientific research.



Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space (2018)

DETAILS

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Summary

This report, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, of the National Academies of Sciences, Engineering, and Medicine's 2017-2027 decadal survey for Earth science and applications from space (ESAS 2017) is the second such decadal survey of the National Academies. This summary provides a comprehensive overview of the present decadal survey and its key findings and recommendations; however, readers should note that space limitations do not permit a detailed discussion of each of the report's 17 findings and 20 recommendations.

EARTH OBSERVATION FROM SPACE: A TRANSFORMATIVE CAPABILITY

From the time of the earliest humans, knowledge about Earth has been fundamental to our fate and prospects. Over the past 60 years, particularly rapid progress has been achieved in acquiring such scientific and practical knowledge, due in large part to the special perspective provided by "satellite-based Earth observations."

The vantage point of space enables us to see the extent to which Earth's ever-changing processes influence our lives. These processes operate at local spatial scales, such as the flows of rivers that provide freshwater and the weather and climate conditions that determine crop yields, as well as at global spatial scales, such as changes in the ocean currents that impact commercial fishing and contribute to global change and climate variability. The space-based vantage point also ensures that we can observe processes occurring over a wide range of time scales, from the abrupt (such as earthquakes) to the decadal (such as growth and shrinkage of the world's great ice sheets), and at all time scales in between.

Empowered by this perspective, we are coming to recognize the complex and continually changing ways by which Earth's processes occur, along with the critical roles their observation and understanding play throughout our lives.

Finding 1.1: Space-based Earth observations provide a global perspective of Earth that has

- Over the last 60 years, transformed our "scientific understanding" of the planet, revealing it to be an integrated system of dynamic interactions between the atmosphere, ocean, land, ice, and human society across a range of spatial and temporal scales, irrespective of geographic, political, or disciplinary boundaries.

- In the past decade in particular, enabled "societal applications" that provide tremendous value to individuals, businesses, the nation, and the world. Such applications are growing in breadth and depth, becoming an essential information infrastructure element for society as they are integrated into people's daily lives.

THRIVING ON OUR CHANGING PLANET

This ability to observe our planet comprehensively matters to each of us. Earth information—for use in Internet maps, daily weather forecasts, land-use planning, transportation efficiency, and agricultural productivity, to name a few—is central to our lives, providing substantial contributions to our economies, our national security, and our personal safety. It helps ensure we are a ***thriving*** society.

The Earth information we have come to rely on throughout our daily lives is the result of a sustained commitment to both exploratory and applied Earth science, and to what has become a sophisticated national and international infrastructure of observing systems, scientific research, and applications. A particular strength of the Earth science and applications field is the extent to which curiosity-based science is inextricably integrated with applications-oriented science and societal benefits. Ongoing commitment to this inspirational and practical science has returned benefits to society many times over, and will continue to do so with further support.

Among the most intellectually and practically important revelations from the past 60 years of space-based observation is the extent to which *Earth is* ***changing****, in multiple ways and for many reasons*. Daily changes, such as weather, were obvious to even the earliest humans, even if not explainable. Longer-term changes, particularly those occurring on global scales, are only now becoming understood and gaining public recognition. Some of these changes are climate related, such as alteration of the El Niño Southern Oscillation (ENSO), but many are not. In addition to climate, changes in air quality, water availability, agricultural soil nutrients, and other Earth resources are being driven largely by human actions. Successfully managing risks and identifying opportunities associated with these changes requires a clear understanding of both the human-driven and the natural processes that underlie them.

A CHALLENGING VISION FOR THE DECADE AND BEYOND

A changing Earth is one we can never understand just from past experience. Its evolving and emerging characteristics must be continually explored through observation. Our scientific curiosity must seek and reveal the new and altered processes that will result from change, if we are to continue applying our knowledge effectively for society's benefit. Decisions we make this decade will be pivotal for predicting the potential for future changes and for influencing whether and how those changes occur. Embracing this new paradigm of understanding a changing Earth, and building a program to address it, is our major challenge for the coming decade and beyond.

Recommendation 2.1: Earth science and applications are a key part of the nation's information infrastructure, warranting a U.S. program of Earth observations from space that is robust, resilient, and appropriately balanced. NASA, NOAA, and USGS, in collaboration with other interested U.S. agencies, should ensure efficient and effective use of U.S. resources by strategically coordinating and advancing this program at the national level, as also recommended in the 2007 Earth Science and Applications from Space (ESAS) decadal survey.

This context of both societal need and intellectual opportunity provided the basis for developing the Earth observation program proposed in this report. Society's fundamental desire to thrive, the expanding scientific knowledge needed to support that desire, and the growing capacity to apply that knowledge are all central motivations for this committee's recommendations. Embracing the goal of understanding Earth in pursuit of this vision—*to thrive on our changing planet*—motivates a new paradigm for the coming decade and beyond.

Earth Science and Applications Paradigm for the Coming Decade

Earth science and derived Earth information have become an integral component of our daily lives, our business successes, and society's capacity to thrive. Extending this societal progress requires that we focus on understanding and reliably predicting the many ways our planet is changing.

A STRUCTURED APPROACH TO ACHIEVING PROGRESS

The next decade is one in which progress will not come easily. Financial and human resource constraints are likely to present challenges to progress (Chapter 1). Succeeding compels NASA, NOAA, and USGS to develop, adopt, and implement strategies to advance both technology and programmatic processes. The committee recommends eight elements (numbered only for identification) of a suggested *strategic framework* (Chapter 2):

1. Commit to sustained science and applications;
2. Embrace innovative methodologies for integrated science/applications;
3. Amplify the cross-benefit of science and applications;
4. Leverage external resources and partnerships;
5. Institutionalize programmatic agility and balance;
6. Exploit external trends in technology and user needs;
7. Expand use of competition; and
8. Pursue ambitious science, despite constraint.

The challenges ahead, and the need for innovative and strategic thinking to overcome them, are reflected in the following community challenge.

Decadal Community Challenge

Pursue increasingly ambitious objectives and innovative solutions that enhance and accelerate the science/applications value of space-based Earth observation and analysis to the nation and to the world in a way that delivers great value, even when resources are constrained, and ensures that further investment will pay substantial dividends.

The committee believes that meeting the challenge described earlier will motivate the scientific community to pioneer *novel approaches* in how it conducts its scientific research, with an emphasis on programmatic and technological innovation to accomplish more with less, with greater attention to the potential benefits of domestic and international partnerships along with the growing capability of commercial sources (Chapters 3 and 4).

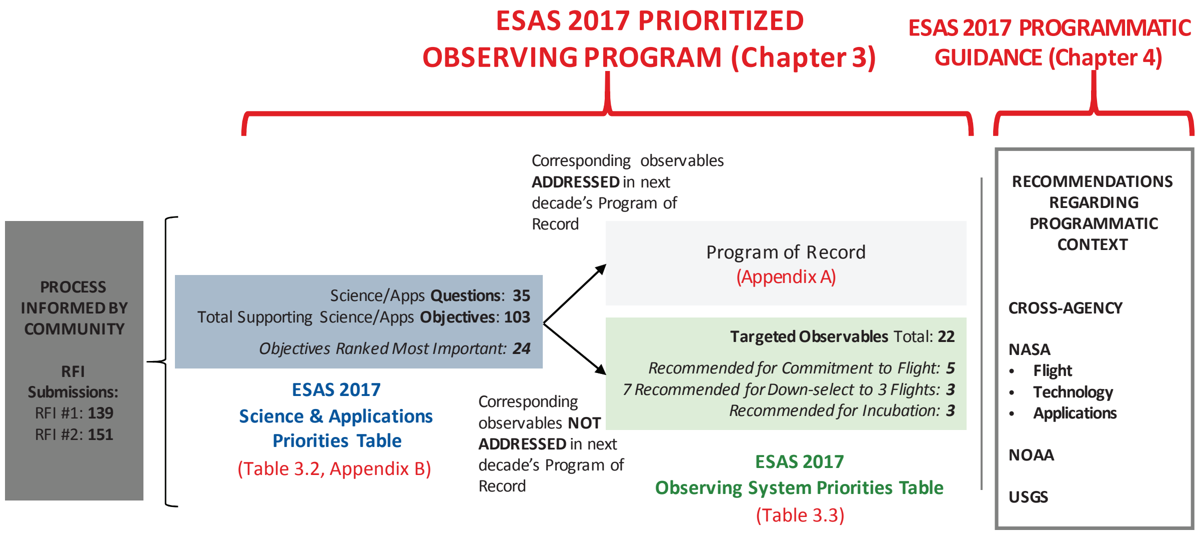

FIGURE S.1 Roadmap for the 2017 Earth Science and Applications from Space (ESAS 2017) decadal survey report based on the survey committee's approach to identifying priorities for the coming decade, starting from community requests for information (RFIs), refining this input to determine priority science and applications questions and objectives, and then identifying new observing system priorities (assuming completion of the program of record). These priorities are complemented by programmatic recommendations.

The committee conducted its work in close collaboration with the decadal survey's five study panels, each interdisciplinary and together spanning all of the disciplines associated with Earth system science. The survey process is summarized in Figure S.1. It was designed to converge—from a large number of community-provided possibilities—to a final, small set of Science and Applications Priorities (shown in blue) and Observing System Priorities (shown in green) that are required to address the nation's Earth science and applications needs. *This process assumed that the existing and planned instruments in the Program of Record (POR) are implemented as expected.*

ESTABLISHING SCIENCE AND APPLICATIONS PRIORITIES

Starting from an initial set of 290 community-submitted ideas, the five interdisciplinary panels, and then the committee narrowed this large set of ideas to a set of *35 key Earth science and applications questions* to be addressed over the next decade. Together, these questions comprehensively address those areas for which advances are most needed in both curiosity-driven and practically focused Earth science and the corresponding practical uses of Earth information. To identify the observational capabilities required to answer these questions, the committee then defined a set of underlying science and applications objectives, evaluating and assigning each to one of three prioritization categories: Most Important (MI), Very Important (VI), and Important (I).

This process informed the committee's Recommendation 3.1 that NASA, NOAA, and USGS pursue the key science and applications questions summarized in Table S.1 (and described in more detail in the body

TABLE S.1 Science and Applications Priorities for the Decade 2017-2027 (see note following table for description)

Science and Applications Area	Science and Applications Questions Addressed by Most Important Objectives
Coupling of the Water and Energy Cycles	**(H-1)** How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods? **(H-2)** How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally, and globally, and what are the short- and long-term consequences?
Ecosystem Change	**(E-1)** What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space? **(E-2)** What are the fluxes (of carbon, water, nutrients, and energy) *between* ecosystems and the atmosphere, the ocean, and the solid Earth, and how and why are they changing? **(E-3)** What are the fluxes (of carbon, water, nutrients, and energy) *within* ecosystems, and how and why are they changing?
Extending and Improving Weather and Air Quality Forecasts	**(W-1)** What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean, and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations? **(W-2)** How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months? **(W-4)** Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do? **(W-5)** What processes determine the spatiotemporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?
Reducing Climate Uncertainty and Informing Societal Response	**(C-2)** How can we reduce the uncertainty in the amount of future warming of the Earth as a function of fossil fuel emissions, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?
Sea-Level Rise	**(C-1)** How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage? **(S-3)** How will local sea level change along coastlines around the world in the next decade to century?
Surface Dynamics, Geological Hazards, and Disasters	**(S-1)** How can large-scale geological hazards be accurately forecasted in a socially relevant time frame? **(S-2)** How do geological disasters directly impact the Earth system and society following an event? **(S-4)** What processes and interactions determine the rates of landscape change?

Very Important (Summarized)	Important (Summarized)
(H-4) Influence of water cycle on natural hazards and preparedness **(W-3)** Influence of Earth surface variations on weather and air quality **(C-3)** Impacts of carbon cycle variations on climate and ecosystems **(C-4)** Earth system response to air-sea interactions **(C-5)** Impact of aerosols on global warming **(C-6)** Improving seasonal to decadal climate forecasts **(C-7)** Changes in decadal scale atmospheric/ocean circulation and impacts **(C-8)** Consequence of amplified polar climate change on Earth system	**(H-3)** Freshwater availability and impacts on ecosystems/society **(W-6)** Long-term air pollution trends and impacts **(W-7)** Processes influencing tropospheric ozone and its atmospheric impacts **(W-8)** Methane variations and impacts on tropospheric composition and chemistry **(W-9)** Cloud microphysical property dependence on aerosols and precipitation **(W-10)** Cloud impacts on radiative forcing and weather predictability **(E-4)** Quantifying carbon sinks and their changes **(E-5)** Stability of carbon sinks

TABLE S.1 Continued

Very Important (Summarized)	Important (Summarized)
(S-5) How energy flows from the core to Earth's surface **(S-6)** Impact of deep underground water on geologic processes and water supplies	**(C-9)** Impacts of ozone layer change **(S-7)** Improving discovery of energy, mineral, and soil resources

NOTE: The highest-priority questions (defined as those associated with Most Important objectives) are listed in full; other questions associated with Very Important or Important objectives are briefly summarized. No further priority is assumed within categories, and the topics are listed alphabetically. Letter and number combinations in parentheses refer to the panel (H = Hydrology, W = Weather, E = Ecosystems, C = Climate, S = Solid Earth) and the numbering of each panel's questions. Complete versions of this table are provided in Table 3.2 and in Appendix B.

of the report; complete versions of this table are provided in Table 3.2 and Appendix B). These questions address the central science and applications priorities for the coming decade.

Recommendation 3.1: NASA, NOAA, and USGS, working in coordination, according to their appropriate roles and recognizing their agency mission and priorities, should implement an integrated programmatic approach to advancing Earth science and applications that is based on the *questions and objectives* listed in Table 3.2, "Science and Applications Priorities for the Decade 2017-2027."

By pursuing these priorities, important advances will be made in areas that are both scientifically challenging and of direct impact to how we live. A major component of the committee's observing program recommendations is a commitment to a set of observation capabilities, outlined in the next section that will enable substantial progress in all of the following science and applications areas:

- Providing critical information on the *make-up and distribution of aerosols and clouds*, which in turn improve predictions of future climate conditions and help us assess the impacts of aerosols on human health;
- Addressing key questions about how *changing cloud cover and precipitation* will affect climate, weather, and Earth's energy balance in the future, advancing understanding of the movement of air and energy in the atmosphere and its impact on weather, precipitation, and severe storms;
- Determining the extent to which the *shrinking of glaciers and ice sheets*, and their contributions to sea-level rise, is accelerating, decelerating, or remaining unchanged;
- Quantifying *trends in water stored on land* (e.g., in aquifers) and the implications for issues such as water availability for human consumption and irrigation;
- Understanding *alterations to surface characteristics and landscapes* (e.g., snow cover, snowmelt, landslides, earthquakes, eruptions, urbanization, land-cover, and land use) and the implications for applications such as risk management and resource management;
- Assessing the *evolving characteristics and health of terrestrial vegetation and aquatic ecosystems*, which is important for understanding key consequences such as crop yields, carbon uptake, and biodiversity; and
- Examining *movement of land and ice surfaces* to determine, in the case of ice, the likelihood of rapid ice loss and significantly accelerated rates of sea-level rise, and in the case of land, changes in strain rates that impact and provide critical insights into earthquakes, volcanic eruptions, landslides, and tectonic plate deformation.

In addition, the committee is proposing competitive observational opportunities, also outlined in the next section, to address at least three of the following science and applications areas:

- Understanding the *sources and sinks of carbon dioxide and methane* and the processes that will affect their concentrations in the future;
- Understanding *glacier and ice sheet contributions to rates of sea-level rise* and how they are likely to impact sea-level rise in the future;
- Improving understanding of *ocean circulation*, the exchanges between the ocean and atmosphere, and their impacts on weather and climate;
- Assessing *changes in ozone and other gases* and the associated implications for human health, air quality, and climate;
- Determining the *amount and melt rates of snow* and the associated implications for water resources, weather, climate, flooding, drought, and so on;
- Quantifying biomass and characterizing ecosystem structure to assess *carbon uptake from the atmosphere and changes in land cover* and to support resource management; and
- Providing critical insights into the *transport of pollutants, wind energy, cloud processes, and how energy moves* between the land or ocean surfaces and the atmosphere.

The recommended program will advance scientific knowledge in areas that are ripe for discovery and that have direct impact on the way we live today. The knowledge developed in the coming decade, through this science, holds great promise for informing actions and investments for a successful future.

IMPLEMENTING AN INNOVATIVE OBSERVING PROGRAM

Addressing the committee's priority science and applications questions requires an ongoing commitment to existing and planned instruments and satellites in the POR. The committee's recommended observing program builds from this, filling gaps in the POR where observations are needed to address the key science and applications objectives for the coming decade. This observing program is summarized in Table S.2 (Table 3.3 in Chapter 3) and in the accompanying Recommendation 3.2. Most observables are allocated to two new NASA flight program elements: a committed group of observations termed "Designated," along with a competed group termed "Earth System Explorer." Within these two new flight program elements, eight of the priority observation needs from Table S.2 are expected to be implemented as instruments, instrument suites, or missions. In addition, several observables are assigned to a new program element called "Incubation," intended to accelerate readiness of high-priority observables not yet feasible for cost-effective flight implementation. Finally, an expansion of the Venture program is proposed for competed small missions to add a focus on continuity-driven observations. Together, these new program elements complement existing NASA flight program elements such as the Venture program.

The foundational observations in Table S.2—the five shown in the "Designated" column that are recommended specifically by the committee for implementation, and the three to be competitively selected from among the identified set of seven "Earth System Explorer" candidates—augment the existing POR and ensure that the survey's 35 priority science and applications questions can be effectively addressed, to the extent that resources allow. In keeping with the study's statement of task, specific missions and instruments were not identified, ensuring that the sponsoring agencies will have discretion for identifying the most cost-effective and appropriate space-based approaches to implementing the recommended set of observations. Each of the new NASA flight program elements promises innovative means for using

TABLE S.2 Observing System Priorities (see note following table for description)

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Aerosols	*Aerosol properties, aerosol vertical profiles, and cloud properties* to understand their effects on climate and air quality	Backscatter lidar and multichannel/multiangle/ polarization imaging radiometer flown together on the same platform	X		
Clouds, Convection, and Precipitation	*Coupled cloud-precipitation state and dynamics* for monitoring global hydrological cycle and understanding contributing processes including cloud feedback	Dual-frequency radar, with multifrequency passive microwave and sub-mm radiometer	X		
Mass Change	*Large-scale Earth dynamics* measured by the changing mass distribution within and between the Earth's atmosphere, oceans, groundwater, and ice sheets	Spacecraft ranging measurement of gravity anomaly	X		
Surface Biology and Geology	*Earth surface geology and biology*, ground/water temperature, snow reflectivity, active geologic processes, vegetation traits, and algal biomass	Hyperspectral imagery in the visible and shortwave infrared (IR), multi- or hyperspectral imagery in the thermal IR	X		
Surface Deformation and Change	*Earth surface dynamics* from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	X		
Greenhouse Gases	*CO_2 and methane fluxes and trends*, global and regional with quantification of point sources and identification of sources and sinks	Multispectral shortwave IR and thermal IR sounders; or lidar*		X	
Ice Elevation	*Global ice characterization* including elevation change of land ice to assess sea-level contributions and freeboard height of sea ice to assess sea ice/ocean/atmosphere interaction	Lidar*		X	
Ocean Surface Winds and Currents	*Coincident high-accuracy currents and vector winds* to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift	Doppler scatterometer		X	
Ozone and Trace Gases	*Vertical profiles of ozone and trace gases* (including water vapor, CO, NO_2, methane, and N_2O) globally and with high spatial resolution	UV/VIS/IR microwave limb/nadir sounding and UV/VIS/IR solar/ stellar occultation		X	
Snow Depth and Snow Water Equivalent	*Snow depth and snow water equivalent*, including high spatial resolution in mountain areas	Radar (Ka/Ku band) altimeter; or lidar*		X	
Terrestrial Ecosystem Structure	*3D structure of terrestrial ecosystem* including forest canopy and aboveground biomass and changes in aboveground carbon stock from processes such as deforestation and forest degradation	Lidar*		X	
Atmospheric Winds	*3D winds in troposphere/planetary boundary layer (PBL)* for transport of pollutants/carbon/aerosol and water vapor, wind energy, cloud dynamics and convection, and large-scale circulation	Active sensing (lidar, radar, scatterometer); or passive imagery or radiometry-based atmospheric motion vectors (AMVs) tracking; or lidar*		X	X

TABLE S.2 Continued

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Planetary Boundary Layer	*Diurnal 3D PBL thermodynamic properties and 2D PBL structure* to understand the impact of PBL processes on weather and air quality through high vertical and temporal profiling of PBL temperature, moisture, and heights	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL lidar; and lidar* for PBL height			X
Surface Topography and Vegetation	*High-resolution global topography*, including bare surface land topography, ice topography, vegetation structure, and shallow water bathymetry	Radar; or lidar*			X

* Could potentially be addressed by a multifunction lidar designed to address two or more of the Targeted Observables

Other ESAS 2017 Targeted Observables, Not Allocated to a Flight Program Element

Aquatic-Coastal Biogeochemistry	Radiance Inter-calibration	Surface Water Height
Magnetic Field Changes	Salinity	
Ocean Ecosystem Structure	Soil Moisture	

NOTE: Observations (Targeted Observables) identified by the steering committee as needed in the coming decade, beyond what is in the Program of Record, allocated as noted in the last three columns (and color-coded) to three new NASA flight program elements (*Designated*, *Earth System Explorer*, *Incubation*; as defined in the accompanying text). Within categories, the targeted observables are listed alphabetically. Targeted Observables included in the original priority consideration but not allocated to a program element are listed at the bottom of the table (see Appendix C for a complete summary).

competition and other programmatic tools to increase the cadence and quality of flight programs, while optimizing cost and risk.

Recommendation 3.2: NASA should implement a set of space-based observation capabilities based on this report's proposed program (which was designed to be affordable, comprehensive, robust, and balanced) by implementing its portion of the Program of Record and adding observations described in Table 3.3, "Observing System Priorities." The implemented program should be guided by the budgetary considerations and decision rules contained in this report and accomplished through five distinct program elements:

1. ***Program of Record.*** **The series of existing or previously planned observations, which must be completed as planned. Execution of the ESAS 2017 recommendation requires that the total cost to NASA of the Program of Record flight missions from fiscal year (FY) 2018 through FY 2027—October 1, 2017 through September 30, 2027—be capped at $3.6 billion.**
2. ***Designated.*** **A program element for ESAS-designated cost-capped medium- and large-size missions to address observables essential to the overall program, directed or competed at the discretion of NASA.**
3. ***Earth System Explorer.*** **A *new* program element involving competitive opportunities for cost-capped medium-size instruments and missions serving specified ESAS-priority observations.**

4. ***Incubation*. A *new* program element, focused on investment for priority observation capabilities needing advancement prior to cost-effective implementation, including an innovation fund to respond to emerging needs.**
5. ***Earth Venture*. Earth Venture program element, as recommended in ESAS 2007, with the addition of a *new* Venture-continuity component to provide opportunity for low-cost sustained observations.**

The committee is confident, based on analyses of technical readiness and cost performed during the study, that the recommended observations have feasible implementations that can be accomplished on schedule and within the stated cost caps. The proposed program was designed both to fit within anticipated budgets (assumed for the purposes of this report to grow only with inflation) and to ensure balance in the mission portfolio among program elements (Figure S.2). As appropriate, candidate instruments and missions were formally subjected to a Cost Assessment and Technical Evaluation (CATE) to assess budget needs. The committee considered management of development cost to be of critical importance to effective implementation of this program, in order to avoid impacting other programs and altering the desired programmatic balance. Should budgets be more or less than anticipated, the report includes decision rules for altering plans in a manner that seeks to ensure the overall program integrity.

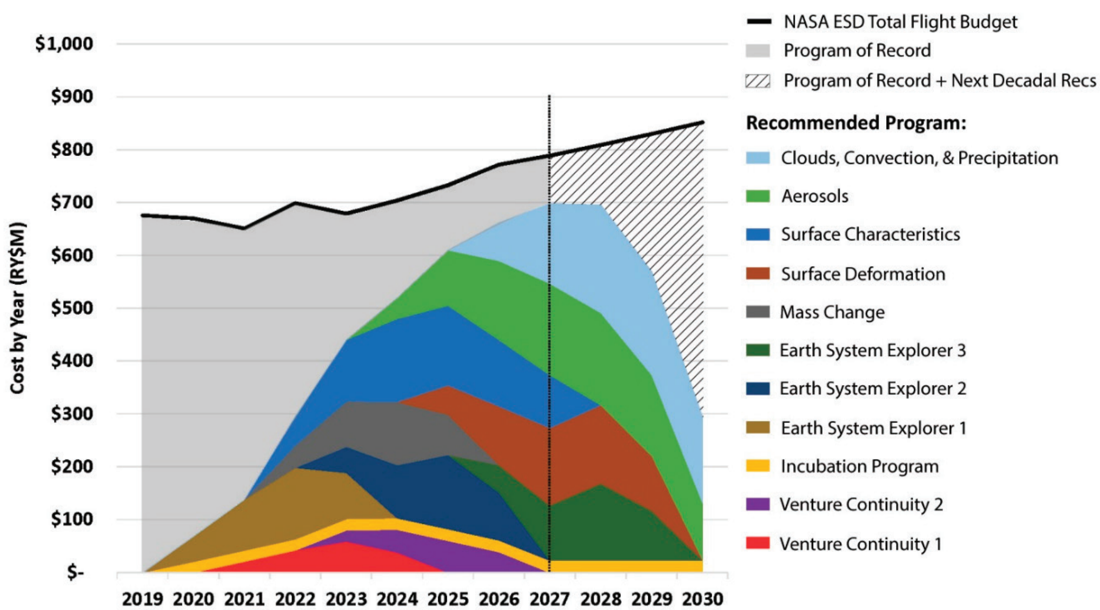

FIGURE S.2 The 2017 Earth Science and Applications from Space (ESAS 2017) real-year dollar estimated costs (colored wedges), broken down by NASA flight program element proposed in this report, as compared to the anticipated flight budget (black line), showing how the ESAS 2017 costs fit within the available $3.4 billion budget through 2027. The total NASA budget for flight elements assumes growth at the rate of inflation for years beyond the current budget projection. Only the investments related to ESAS 2017 recommendations are shown. The gap between the estimated costs and the available budget represents funds that have been committed to other non-ESAS mission-related activities.

ENABLING THE PROGRAM

Finally, none of this happens without "robust supporting programs" at NASA, NOAA, and USGS that provide the enabling resources for developing the recommended space-based observing systems and evaluating the data they produce. In particular, these supporting programs are central to transforming scientific advances into applications and societal benefits. The committee has proposed a variety of programmatic actions intended to improve the ability of each agency to deliver on its space-based observation programs.

Key among these are findings and recommendations associated with the following: ensuring balanced and robust programmatic structures (Findings 4.4 and 4.5); recognizing the importance of sustained land imaging through the USGS Landsat program (Finding 4.10); and leveraging partnering opportunities (such as the European Union's Copernicus/Sentinel program noted in Recommendation 4.5) that enhance operational efficiencies and ensure that the agencies can accomplish the most possible within their available resources (Finding 4.10; Recommendations 4.5, 4.11, and 4.12).

Finding 4.4: A robust and resilient Earth Science Division (ESD) program has the following attributes**:**

- A healthy cadence of small/medium missions to provide the community with regular flight opportunities, to leverage advances in technologies and capabilities, and to rapidly respond to emerging science needs;
- A small number of large cost-constrained missions, whose implementation does not draw excessive resources from smaller and more frequent opportunities;
- Strong partnerships with U.S. government and non-U.S. space agencies;
- Complementary programs for airborne, in situ, and other supporting observations;
- Periodic assessment of the return on investment provided by each program element; and
- A robust mechanism for trading the need for continuity of existing measurement against new measurements.

Finding 4.5: Maximizing the success of NASA's Earth science program requires balanced investments across its program elements, each critically important to the overall program. The *flight* program provides observations that the *research and analysis* program draws on to perform scientific exploration, the *applied sciences* program transforms the science into real-world benefits, and the *technology* program accelerates the inclusion of technology advances in flight programs. The current balance across these four program elements is largely appropriate, enabling a robust and resilient Earth science program, and can be effectively maintained using decision rules such as recommended in this report. Some adjustment of balance within each program element is warranted, as recommended in this report.

Finding 4.10: Extension of Landsat capability through synergy with other space-based observations opens new opportunities for Landsat data usage, as has been demonstrated with the European Space Agency (ESA) through cross-calibration and data sharing for Sentinel-2. These successes serve as a model for future partnerships and further synergies with other space-based observations.

Recommendation 4.5: Because expanded and extended international partnerships can benefit the nation:

- **NASA should consider enhancing existing partnerships and seeking new partnerships when implementing the observation priorities of this decadal survey.**
- **NOAA should strengthen and expand its already strong international partnerships, by (1) coordinating with partners to further ensure complementary capabilities and operational backup while**

minimizing unneeded redundancy; and (2) extending partnerships to the more complete observing system life cycle that includes scientific and technological development of future capabilities.

- **USGS should extend the impact of the Sustainable Land Imaging (SLI) program through further partnerships such as that with the European Sentinel program.**

Recommendation 4.11: NOAA should establish itself among the leading government agencies that exploit potential value of commercial data sources, assessing both their benefits and risks in its observational data portfolio. It should innovate new government/commercial partnerships as needed to accomplish that goal, pioneer new business models when required, and seek acceptable solutions to present barriers such as international partner use rights. NOAA's commercial data partnerships should ensure access to needed information on data characteristics and quality as necessary and appropriate, and be robust against loss of any single source/provider if the data are essential to NOAA core functions.

Recommendation 4.12: NOAA should establish, with NASA, a flexible framework for joint activities that advance the capability and cost-effectiveness of NOAA's observation capabilities. This framework should enable implementation of specific project collaborations, each of which may have its own unique requirements, and should ensure (1) clear roles, (2) mutual interests, (3) life-cycle interaction, (4) multi-disciplinary methodologies, (5) multielement expertise, and (6) appropriate budget mechanisms.

ANTICIPATED PROGRESS WITHIN THE DECADE

In this report, the committee identifies the science and applications, observations, and programmatic support needed to bring to fruition its vision of understanding deeply the nature of our changing planet. With implementation of its recommended plan, the committee expects the following to have been accomplished by the end of the survey decade:

Programmatic implementation within the agencies will be made more efficient by

- *Increasing Program Cost-Effectiveness.* Promote expanded competition with medium-size missions to take better advantage of innovation and leveraged partnerships.
- *Institutionalizing Sustained Science Continuity*. Establish methods to prioritize and facilitate the continuation of observations deemed critical to monitoring societally important aspects of the planet, after initial scientific exploration has been accomplished.
- *Enabling Untapped NASA-NOAA Synergies.* Establish more effective means for NASA-NOAA partnership to jointly develop the next generation of weather instruments, accelerating NOAA's integration of advanced operational capabilities.

Improved observations will enable exciting new science and applications by

- *Initiating or Deploying More Than Eight New Priority Observations of Our Planet.* Develop or launch missions and instruments to address new or extended priority observation areas that serve science and applications. Five are prescribed in the committee's recommended program for NASA, and three are to be chosen from among seven candidate areas prioritized by the committee to form the basis of a new class of NASA competed medium-size missions. These new observation priorities will be complemented by an additional two new small missions and six new instruments to be selected through NASA's existing Earth Venture program element, and two opportunities for sustained observations to be selected through the new Venture-Continuity strand of this program. The existing and planned POR will also be implemented as expected.

- *Achieving Breakthroughs on Key Scientific Questions.* Advance knowledge throughout portions of the survey's 35 key science questions (Table S.1, above) that address critical unknowns about the Earth system and promise new societal applications and benefits.

Businesses and individuals will receive enhanced value from scientific advances and improved Earth information, such as

- *Increased Benefits to Operational System End-Users.* Enhanced processes and tools to leverage lost-cost commercial and international space-based observations will allow NOAA and USGS to have greater impact on the communities they serve.
- *Accelerated Public Benefits of Science.* Improved capacity for transitioning science to applications will make it possible to more quickly and effectively achieve the societal benefits of scientific exploration, generating applications more responsive to evolving societal needs.
- *Development of Innovative Commercial Applications.* New observations and data products enable innovative commercial applications that have the potential for substantial economic benefit to both developers and end users.

Building on the success and discoveries of the past several decades, this report's balanced program provides a pathway to realizing remarkable scientific and societal benefits from space-based Earth observations. It ensures that the United States will *continue to be a visionary leader and partner* in Earth observation over the coming decade, inspiring the next generation of Earth science and applications innovation and the people who make that possible.