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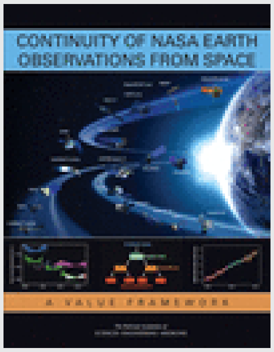

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CONTINUITY OF NASA EARTH OBSERVATIONS FROM SPACE

A VALUE FRAMEWORK

Committee on a Framework for Analyzing the Needs for Continuity of
NASA-Sustained Remote Sensing Observations of the Earth from Space

Space Studies Board

Division on Engineering and Physical Sciences

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COMMITTEE ON A FRAMEWORK FOR ANALYZING THE NEEDS FOR CONTINUITY OF NASA-SUSTAINED REMOTE SENSING OBSERVATIONS OF THE EARTH FROM SPACE

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[1] Through June 20, 2014.
[2] From September 22, 2014.
[3] From September 29, 2014 to March 27, 2015.
[4] From October 6, 2014 to December 12, 2014.

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Preface

In a highly constrained budgetary environment, NASA, like all federal agencies, is faced with difficult choices among competing priorities for investment. Within NASA's Earth Science Division (ESD), part of the Science Mission Directorate, these choices include whether to invest in the continuation of a particular existing data stream versus another (including, but not limited to, climate-related measurements), or to develop a new measurement capability sought by research and applications communities. None of these choices is straightforward; for example, prioritizing among competing "continuity" measurements requires a uniform valuation method and a rigorous understanding of how that value evolves over time, including the implications of a data gap.

In 2013, at the request of ESD, an ad hoc committee of the National Research Council (NRC)[1] was formed with the task of providing a framework to assist in the determination of when a measurement(s) or data set(s) initiated by ESD should be collected for extended periods. In particular, and considering the expected constrained budgets for the NASA Earth science program, the committee was asked to:

1. Provide working definitions of, and describe the roles for "continuity" for the measurements and data sets ESD initiates and uses to accomplish Earth system science objectives; and
2. Establish methodologies and/or metrics that NASA can use to inform strategic programmatic decisions regarding the scope and design of its observation and processing systems.

In carrying out its task, the committee focused on developing a decision framework that allows prioritization of measurements based on their scientific value. In addition, the committee identified, defined, and evaluated a small set of key measurement characteristics to illustrate the framework concept. In its report, the committee presents two notional evaluation frameworks that may be broadly categorized as qualitative and quantitative. The qualitative framework has an analog in the proposal review process that NASA currently employs while the quantitative framework—a decision approach that is the subject of this report—was developed to provide more rigor to an inherently subjective decision-making process. Though the committee's quantitative framework also requires inputs that are subjective, they enter the framework in a transparent manner and the sensitivity of the calculated "value" to variations in the inputs is easily seen.

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The committee recognizes an important qualification regarding its treatment of task item 2, above: As explained in the report, the proposed quantitative decision framework can be adapted to include choices between the continuation of an existing measurement and the initiation of a new measurement, or choices among measurements focused on societal-benefit applications. *However, the framework it presents is by design directed toward choices among extended missions undertaken for research purposes aimed at quantifying global change.* The committee endeavored to provide a more general response to task item 2; however, it found that development of even the simpler "apples-to-apples" decision framework for the measurements highlighted above in italics to be extremely challenging. Finally, the committee acknowledges the limitations of its approach. While the proposed methodology can inform measurement choices based on their value to achieving a quantified science objective, it does not capture non-quantifiable objectives such as increasing the knowledge and experience base to facilitate the development of a new remote sensing capability.

The report from the ad hoc committee is presented here; it is organized as follows:

Chapter 1—Introduction—provides background relevant to the committee's task;

Chapter 2—Measurement Continuity—includes the committee's working definition of measurement continuity; a discussion of the four criteria—instrument calibration uncertainty, repeatability, time and space sampling, and data systems and delivery for climate variables (algorithms, reprocessing, and availability)—that are used in a framework to determine whether a data set has the requisite quality for long-term Earth observations and global change research; and the introduction of the "quantified objective" that is central to the committee's methodology;

Chapter 3—A Decision Framework for NASA Earth Science Continuity Measurements—presents a quantitative framework that can be applied to "value" competing choices for measurement continuity;

Chapter 4—Applying the Framework to Continuity Measurements—provides an overview of the application of the framework; and

Appendixes—Appendixes B-G provide comprehensive illustrations of the framework applied to several representative quantified Earth science objectives. Also in the appendixes are the full task statement (Appendix A), biographical information for committee members (Appendix H), and a list of acronyms (Appendix I).

A note on terminology: When characterizing a measurement, the committee uses terms such as uncertainty, repeatability, accuracy, and precision in a manner consistent with the definitions provided in reference guides published by the National Institute of Standards and Technology (NIST). For example, NIST defines "uncertainty" as a "parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand [which is the property that is the object of measurement]." Similarly, NIST defines repeatability (of results of measurements) as the "closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement."[2] In this report, the "combined standard uncertainty" is obtained by combining the individual uncertainties, including those evaluated by statistical methods (what the committee terms Type A) and those evaluated by other means (Type B). The committee uses "stability" in the context of the normal dictionary definition—"the quality or state of something that is not easily changed"—whereas repeatability applies to all components that translate a measurement (or measurements) to a geophysical quantity (or qualities) that pertain to a specified quantified science objective. Most often, it refers to the instrument calibration, which carries through all processing levels.

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[2] See "Measurement Uncertainty," a publication of the NIST Information Technology Laboratory available online at http://www.nist.gov/itl/sed/gsg/uncertainty.cfm. Also see Appendix D, "Terminology," in B.N. Taylor and C.E. Kuyatt, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297, 1994 Edition, http://www.nist.gov/pml/pubs/tn1297/index.cfm. Another useful reference is G. Ohring, B. Wielicki, R. Spencer, B. Emery, and R. Datla, eds., *Satellite Instrument Calibration for Measuring Global Climate Change*, NIST Rep. NISTIR 7047, 2004, http://tinyurl.com/p92bkul.

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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

George H. Born, University of Colorado, Boulder,
Amy J. Braverman, Jet Propulsion Laboratory,
Inez Y. Fung, University of California, Berkeley,
Kristina B. Katsaros, Northwest Research Associates, Inc. (emeritus),
Ralph F. Milliff, University of Colorado, Boulder,
Steven E. Platnick, NASA Goddard Space Flight Center,
Kevin E. Trenberth, National Center for Atmospheric Research,
Eric F. Wood, Princeton University, and
Howard A. Zebker, Stanford University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by James O. Berger, Duke University, and Charles F. Kennel, University of California, San Diego, who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

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Summary

NASA's Earth Science Division (ESD) conducts a wide range of satellite and suborbital missions to observe Earth's land surface and interior, biosphere, atmosphere, cryosphere, and oceans as part of a program to improve understanding of Earth as an integrated system. Earth observations provide the foundation for critical scientific advances, and environmental data products derived from these observations are used in resource management and for an extraordinary range of societal applications, including weather forecasts, climate projections, sea level change, water management, disease early warning, agricultural production, and the response to natural disasters.

As the complexity of societal infrastructure and its vulnerability to environmental disruption increases, the demands for deeper scientific insights and more actionable information continue to rise. To serve these demands, NASA's ESD is challenged with optimizing the partitioning of its finite resources among measurements intended for exploring new science frontiers, carefully characterizing long-term changes in the Earth system, and supporting ongoing societal applications. This challenge is most acute in the decisions the division makes between supporting measurement continuity of data streams that are critical components of Earth science research programs (including, but not limited, to climate-related measurements) and the development of new measurement capabilities.

While the distinction between measurements oriented toward "research" and "applications" is somewhat artificial (both types of measurements are typically needed in support of a particular societal application, and both research and application objectives may require continuous or sustained measurements), their requirements are not consistent. In particular, while many applications are associated with a requirement for near real-time data availability, climate change science objectives typically require accurate measurements and long, stable, uninterrupted time-series. Further, within the class of measurements with a science/research focus, the need for new measurements to enable Earth System process studies contrasts with the need to continue well-understood measurements related to key climate change indicators.

Community guidance to NASA ESD from the first National Research Council (NRC)[1] Earth science and applications from space decadal survey (NRC, 2007) largely focused on new measurements, owing to assumptions made about the role of other agencies in supporting high-priority climate, weather, and land surface continuity measurements. However, for a variety of reasons, including technical and budgetary challenges, some of these assumptions were not met (NRC, 2012). In response to these changes, as well as to guidance from the Administra-

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tion and Congress, NASA's Earth science portfolio has expanded to include new responsibilities for the continuation of several previously initiated measurements that were formerly assigned to other agencies.

As decadal survey recommendations are executed and new capabilities and applications are demonstrated, NASA anticipates an increasing number of measurements and associated instruments and missions will be candidates for follow-ons. The agency's request for the present study (the statement of task is reprinted in Appendix A) recognizes this trend and the importance of establishing a more quantitative understanding of the need for measurement continuity and the consequences of measurement gaps. In addition to requesting a working definition of "continuity," the task statement asks that a decision framework be provided to help optimize the allocation of resources.

This report, from the Committee on a Framework for Analyzing the Needs for Continuity of NASA-Sustained Remote Sensing Observations of the Earth from Space, is the response to these requests. As detailed in the report, the committee recommends to NASA a decision-making framework, based on key continuity characteristics, that effectively discriminates between competing continuity measurements. The recommended framework carries a strong emphasis on quantitative evaluation methods in order to achieve process objectivity and transparency.

In developing a readily implementable framework, the committee focused on climate change science goals where space-based continuity measurements are expected to make substantial contributions. With this specific focus, the recommended framework is intended as a new method for evaluating science-driven continuity missions and represents a complement to the existing NASA proposal evaluation processes for NASA Research Announcements and Earth Venture Announcements of Opportunity.

This framework should be viewed as an initial step toward a more comprehensive methodology. As discussed in the report, modifications to the framework would allow it to be used to establish priorities among new, first-of-a-kind measurements, as well as to examine operational- or applications-based measurements. Developed appropriately, the committee envisions a single comprehensive evaluation approach for both new and continuity measurements, driven by science and/or application objectives.

ELEMENTS OF THE COMMITTEE'S DECISION FRAMEWORK

The committee's approach in developing the desired decision-framework begins with a clear definition of measurement continuity in time and space. Ensuring continuity of a geophysical variable[2] from a sequence of "improved" instruments, or from copies of the same instrument, requires a careful program of calibration, instrument characterization and comparison, and validation. While the vantage point of space facilitates global and repeatable observations of Earth, the development of long-term measurement time-series having small, combined standard uncertainties on multiple spatial scales is particularly challenging. In operational programs, copies of instruments have been flown multiple times with the goal of simplifying this process. Although copies do not eliminate the need for calibration and characterization studies, such an approach—including carefully chosen group procurements of instruments or spacecraft—will reduce costs and typically reduces the risk in providing a long-term continuous record.

The *quality* of a measurement is particularly relevant in the context of continuity and is characterized primarily by its combined standard uncertainty, which is the consequence of instrument calibration uncertainty, repeatability; time and space sampling; and data systems and delivery for climate variables (algorithms, reprocessing, and availability)—each of which depends on the scientific objective. Changes in platform observing characteristics (for example, altitude and local observing time) introduce perturbations into the entire system. Development of calibration methods through mission overlaps, in situ validation, and ground-based calibration traceable to National Institute of Standards and Technology standards are necessary to provide repeatable long-term measurements of geophysical variables.

With this in mind, the committee finds that the following is a sufficient, high-level definition of continuity across the Earth science subdisciplines for use in an analysis framework focused on scientific objectives:

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[2] See Box 2.1 for the committee's definition of geophysical variable and several other terms used in this report.

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Finding: Continuity of an Earth measurement exists when the quality of the measurement for a specific quantified Earth science objective is maintained over the required temporal and spatial domain set by the objective.

The notion of a quantified objective is the starting point for the committee's recommended decision framework. The characteristics of a well-formulated quantified objective are the following:

- It is directly relevant to achieving an overarching science goal of NASA ESD;
- It is presented in such a way that the required measurement(s) and their resolution (spatial, temporal, and radiometric), calibration uncertainty and repeatability, and other requirements have traceability to the overarching science goal; and
- It is expressed in a way that allows an analytical assessment of the importance of the objective to an Earth science goal and the utility of the targeted geophysical variable(s) for meeting the science objective.

Chapter 3 presents several examples of quantified objectives.

Recommendation: Proposed space-based continuity measurements should be evaluated in the context of the quantified Earth science objectives they address.

The committee envisions NASA ESD establishing a small set of quantified objectives from the same sources that inform the development of its program plan, notably the scientific community's consensus priorities expressed in NRC decadal surveys and guidance from the executive and congressional branches. Congressionally mandated midterm assessments of the decadal survey afford an additional opportunity for community evaluation of the objectives. Continuity of an established data set will compete with proposed new measurements as well as multi-measurement "intensives," campaigns that may be mounted to, for example, gain a detailed understanding of a particular climate process. The latter proposals should be defined through a quantified objective that could then be evaluated via the committee's proposed framework or whatever similar quantitative, open, and objective evaluation ESD establishes for continuity measurements.

Recommendation: NASA, which is anticipated to be a principal sponsor of the next decadal survey in Earth science and applications from space, might task the decadal survey with the identification, and possible prioritization, of the quantified Earth science objectives associated with the recommended science goals.

In addition to their research-oriented objectives, Earth observations and their derived information products support numerous user communities within and outside of the government. Extension of the committee's decision framework to measurements focused on societal-benefit applications is desirable but will require expertise outside of the Earth science community to formulate analogous quantified objectives in Earth applications. Toward this end, the committee makes the following recommendation:

Recommendation: NASA should initiate studies to identify and assess quantified Earth applications objectives related to high-priority, societal-benefit areas.

Based on lessons from cost-benefit analysis and decision theory, the committee found that a value-centered framework is capable of effectively distinguishing among the relevant Earth measurements; implemented appropriately, it will achieve an improved degree of openness and transparency. The value-centered approach recommended in this report includes both measurement benefit and affordability considerations. The study identified a

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relatively small set of characteristics that enable a tractable evaluation of benefit, which along with affordability allow discrimination in value among competing measurement/quantified objective pairs.[3] They are:

1. The scientific *importance* (*I*) of the quantified objective;
2. The *utility* (*U*) of a geophysical variable record for achieving a quantified objective;
3. The *quality* (*Q*) of a measurement for providing the desired geophysical variable record; and
4. The *success probability* (*S*) of achieving the measurement and its associated geophysical variable record.
5. The *affordability* (*A*) of providing the measurement and its geophysical variable record.

Additional cross-cutting factors are recognized to impact both benefit and affordability, and methods to treat them appropriately within the framework are discussed in the report. Examples of cross-cutting factors include the ability to leverage other measurement opportunities in pursuit of the science objective and the resilience of a geophysical variable record to unexpected degradation (or gaps) in the measurement quality.

As discussed in the report, the committee finds that the quality metric plays a decisive role in determining when a measurement should be collected for durations longer than the typical lifetimes of single satellite missions. The most critical factor is whether (or not) the combined standard uncertainty of the measurement is sufficient for addressing the quantified objective. A related factor is the impact of a data gap (see Section 3.4.2 in Chapter 3), which itself depends on the measurements calibration uncertainty (i.e., traceability to an absolute scale) as well as on the natural variability of the measurand over the gap's duration. While there are numerous ways to evaluate quality in the context of continuity measurements, a useful quality metric is expected to vary between continuity required for short-term operational use (e.g., weather prediction, hazard warnings, agricultural crop monitoring) versus longer-term science objectives, such as those related to global climate change.[4] Examples for assessing quality are given in Chapter 4.

> **Finding: Assessing the quality of a particular continuity measurement requires knowledge of a measurement's combined standard uncertainty, which is derived from the instrument calibration uncertainty, repeatability, time and space sampling, and data systems and delivery of climate variables (algorithms, reprocessing, and availability), and the consequences of data gaps on the relevant quantified science objective(s).**
>
> **Recommendation: The committee recommends that NASA be responsible for refining the assessment approach for the quality characteristic.**

Evaluation of a measurement's affordability and benefit for decision-making purposes can likely be accomplished through a number of equally valid methods, some of which are examined in this report. Regardless of the evaluation methods that NASA and the community adopt, the application of those methods should make consistent use of well-documented and understood tools and studies, as highlighted in the following recommendations.

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[3] The committee debated at length regarding the choice of framework characteristics; the object was to derive a minimal set of largely independent characteristics (metrics) that would provide meaningful evaluations of proposed continuity measurements. That the factors are not completely independent in a statistical sense is recognized. For example, success probability (*S*) and affordability (*A*) are not completely independent; however, the relationship between them is sufficiently complex that it was necessary to retain both in the framework. As an example: NASA's ability to "buy down" risk (i.e., increase *S* by decreasing *A*) is not easily quantified for complex technologies; similarly, accounting for the strategic plans of other national and international partners—a difficult problem—is easier to handle in a framework with separate success and affordability factors. Accordingly, the committee elected to retain both the success probability and affordability characteristics. By retaining success probability, the treatment of uncertainty in the decision process is more readily achieved.

[4] The committee notes that the quality requirements for measurements related to climate change objectives will often be most stringent at a global scale and less stringent at zonal or regional scales. (Antarctic ozone, regional aerosol change, and polar ice sheets are exceptions where regional anthropogenic signals can be detected before global average signals.) Instrument accuracy and repeatability will, therefore, often be driven by global average analysis as in many of the examples in this report. However, the committee's analysis framework can be used at any spatial scale required by the quantified objective.

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> **Recommendation: NASA should foster a consistent methodology to evaluate the utility of geophysical variables for achieving quantified Earth science objectives. The committee notes that such a methodology could also be utilized by the Earth science decadal survey in its priority recommendations.**

> **Recommendation: NASA should extend their current mission cost tools to address continuity measurement-related costs needed for the decision framework.**

The ability of ESD officials to make informed decisions requires unbiased and consistent information on benefits and affordability that is re-evaluated regularly and presented on a time frame appropriate for NASA planning. The committee advises that inputs to these evaluations be derived from sources such as submitted proposals and face-to-face interactions with measurement advocates.

> **Recommendation: NASA's Earth Science Division should establish a regular process for critical evaluation and modification of quantified objectives in Earth science and applications and their associated measurements.** The committee suggests creating an analog to the senior review of current satellite operations, which uses senior researchers from a range of communities and results in consistent recommendations to the ESD director.

In summary, the committee offers the following recommendation:

> **Recommendation: NASA should establish a value-based decision approach that includes clear evaluation methods for the recommended framework characteristics and well-defined summary methods leading to a value assessment.**

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1

Introduction

Natural and human-induced changes in the Earth system—from our planet's interior to the land surface, ocean, and atmosphere—affect all aspects of life and society. To understand and respond to these changes and develop tools for decision making, Earth system models assimilate foundational observations collected from the land, sea, air, and space (NRC, 2008). NASA, the Department of Commerce (National Oceanic and Atmospheric Administration [NOAA]), and the Department of the Interior (U.S. Geological Survey) are the civil federal agencies with programs that use the vantage point of space to enable these observations, with NASA having a lead role in observations that aim to advance the study of Earth as an integrated dynamic system of chemical, biological, and physical processes—"Earth system science."

NASA's stated purpose of its Earth science program is "the development of a scientific understanding of Earth's system and its response to natural or human-induced changes and to improve prediction of climate, weather, and natural hazards" (NASA, 2014). Within NASA, the Earth Science Division (ESD) is responsible for coordinating satellite and suborbital missions for long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans (NASA, 2014).

ESD develops its observing strategy in consultation with the scientific community and in response to congressional and executive branch direction. A notable expression of the scientific community's overarching objectives for NASA Earth science is found in the 2007 National Research Council (NRC) decadal survey *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (NRC, 2007). By design, the decadal survey involved a broad swath of Earth scientists and end users of information[1] derived from Earth observations. The survey recommendations were thus an expression of a "bottom-up" consensus of research priorities that span disciplinary boundaries; these recommendations are given particular weight within NASA.[2] ESD also responds to direction to NASA from Congress (for example, the restoration in 2009—3 years before scheduled

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[1] The decadal survey attempted to prioritize elements of its observing strategy with relevance to society as the foremost consideration. The survey committee—the authors of the survey report—recommended a national strategy for Earth observations from space whose overarching objective would be "a program of scientific discovery and development of applications that will enhance economic competitiveness, protect life and property, and assist in the stewardship of the planet for this and future generations" (NRC, 2007, p. 2).

[2] See NASA, "Decadal Survey," http://science.nasa.gov/earth-science/decadal-surveys/, accessed August 5, 2014. The 2007 Earth science and applications from space decadal survey (NRC, 2007) will be repeated on an approximately 10-year cycle per Public Law 110-442, the NASA Authorization Act of 2008. Thus, work on the next decadal survey is expected to begin in 2015 and be completed in 2017.

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launch—of the thermal infrared instrument to the Landsat Data Continuity Mission) and the Administration (e.g., the 2010 "climate-centric" architecture; NASA, 2010).

ESD denotes "foundational" missions as missions in development at the time the 2007 NRC decadal survey was published. They include Aquarius, Suomi National Polar-orbiting Partnership (S-NPP), Landsat Data Continuity Mission (LDCM), and the Global Precipitation Measurement (GPM), all of which have been implemented successfully.[3,4] In addition to the foundational missions, ESD is developing new missions based on the recommendations in the 2007 decadal survey (NRC, 2007) and climate continuity missions, which respond to both the recommendations of the decadal survey and the climate-centric architecture (NASA, 2010). These include Soil Moisture Active-Passive (SMAP),[5] which was launched successfully in January 2015; Climate Absolute Radiance and Refractivity Observatory (CLARREO);[6] Ice, Cloud and land Elevation Satellite (ICESat-II);[7] Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI);[8] Hyperspectral Infrared Imager (HyspIRI);[9] Active Sensing of CO_2 Emissions Over Nights, Days, and Seasons (ASCENDS);[10] Surface Water and Ocean Topography (SWOT);[11] Geostationary Coastal and Air Pollution Events (GEO-CAPE);[12] and Aerosol-Clouds-Ecosystems (ACE).[13,14] Earth Venture, also a recommendation of the decadal survey, is now an element of NASA's Earth System Science Pathfinder Program.[15] It consists of low-cost, competed suborbital and orbital missions as well as instruments for Missions of Opportunity. The Climate Continuity missions include: Orbiting Carbon Observatory-2 (OCO-2),[16] Stratospheric Aerosol and Gas Experiment-III (SAGE III),[17] Gravity Recovery and Climate Experiment Follow-on (GRACE-FO),[18] and Pre-Aerosol, Clouds, and Ocean Ecosystem (PACE).[19]

Starting in fiscal year 2014, the Administration directed NASA to assume responsibility for a suite of climate-relevant observations for the purpose of continuing a multi-decadal data record in ozone profiling, Earth radiation budget, and total solar irradiance. These measurements were to have been implemented by NOAA with the Radiation Budget Instrument (RBI) and the Ozone Mapping and Profiler Suite Limb profiler (OMPS-L) on NOAA's Joint Polar Satellite System 2 (JPSS-2) series, and the Total Solar Irradiance Instrument 2 (TSIS-2) instrument flown separately. NASA received a one-time funding increment of $40 million in 2014 for these instruments; however, this is only a fraction of the estimated $200-$300 million cost for their implementation.[20] Further, the Senate Appro-

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[3] NASA, "Missions," http://science.nasa.gov/missions/.

[4] The committee learned after report writing that the Aquarius mission ended in June 2015 following a hardware component failure that resulted in the loss of onboard power regulation and spacecraft attitude stabilization.

[5] NASA, "Soil Moisture Active-Passive (SMAP)," http://science.nasa.gov/missions/smap/. The committee learned after report writing that the L-band radar on SMAP ceased transmission in July 2015. SMAP's L-band radiometer continues to operate normally, and NASA expects most of the mission's science objectives will be met. See "NASA Soil Moisture Radar Ends Operations, Mission Science Continues," September 2, 2015, http://smap.jpl.nasa.gov/news/1247/.

[6] NASA is studying options for lower cost implementation of CLARREO while still achieving a majority of its science objectives; see NASA Langley Research Center (LaRC), "About CLARREO: Mission Concept," http://clarreo.larc.nasa.gov/about-mission.html.

[7] NASA, "Ice, Cloud and land Elevation Satellite (ICESat-II)," http://science.nasa.gov/missions/icesat-ii/.

[8] NASA Jet Propulsion Laboratory (JPL), "Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI)," http://desdyni.jpl.nasa.gov/.

[9] NASA JPL, "Hyperspectral Infrared Imager (HyspIRI)," http://hyspiri.jpl.nasa.gov/.

[10] NASA Goddard Space Flight Center (GSFC), "Active Sensing of CO2 Emissions Over Nights, Days, and Seasons (ASCENDS)," http://decadal.gsfc.nasa.gov/ascends.html.

[11] NASA JPL, "Surface Water and Topography (SWOT)," http://swot.jpl.nasa.gov/.

[12] NASA LaRC, "Geostationary Coastal and Air Pollution Events (GEO-CAPE)," http://geo-cape.larc.nasa.gov/.

[13] NASA GSFC, "Aerosol-Clouds-Ecosystems (ACE)," http://dsm.gsfc.nasa.gov/ace/.

[14] Budget cuts in 2012 forced a revaluation of the DESDynI mission. NASA is now implementing the L-band synthetic aperture radar component of DESDynI as part of NISAR (http://nisar.jpl.nasa.gov/), the NASA-ISRO (Indian Space Research Organisation) SAR Mission.

[15] NASA, "Earth System Science Pathfinder Program," http://science.nasa.gov/about-us/smd-programs/earth-system-science-pathfinder/.

[16] NASA, "Orbiting Carbon Observatory-2 (OCO-2)," http://science.nasa.gov/missions/oco-2/.

[17] NASA, "Stratospheric Aerosol and Gas Experiment–III (SAGE III)," http://science.nasa.gov/missions/sage-3-iss/.

[18] NASA JPL, "Gravity Recovery and Climate Experiment Follow-on (GRACE-FO)," http://www.jpl.nasa.gov/missions/gravity-recovery-and-climate-experiment-follow-on-grace-fo/.

[19] NASA GSFC, "Pre-Aerosol, Clouds, and Ocean Ecosystem (PACE)," http://decadal.gsfc.nasa.gov/pace.html.

[20] Thus, as ESD Director Michael Freilich explained in comments on October 29, 2013, to the NRC Committee on Earth Science and Applications from Space, which was meeting in Washington, D.C., NASA is examining alternative methods that could allow for lower-cost implementation. Also see Leone (2013).

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priations Committee initiated a budget bill (not passed) that directed the development costs and responsibilities for the Deep Space Climate Observatory (DSCOVR) and Jason-3 to be transferred from NOAA to NASA ESD.[21]

As shown in Figure 1.1 and Table 1.1, the Earth Science program's increasing responsibility for sustained continuity measurements occurs against the backdrop of enacted budgets that have been roughly level in recent years. Pressures on the budget also come from a backlog of decadal survey-recommended missions (NRC, 2012) and an increasing demand for Earth observations to support societal applications (NSTC, 2014).

1.1 THE ROLE OF SUSTAINED OBSERVATIONS IN NASA AND NOAA RESEARCH PROGRAMS

Space-borne measurements carried out by NASA ESD are typically categorized as research while the operational space-borne measurements carried out by NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) are frequently referred to as monitoring. This delineation is an artificial characterization because both sets of measurements have and continue to play critical roles in advancing Earth system science. Nowhere is this more evident than in understanding global climate change, where the time scales of "research" are those traditionally ascribed to "monitoring." Depending on the spatial and temporal scales of interest and the nature of the particular process, the climate change "signal" to be detected may be small relative to other sources of variability. For example, attribution of a change in sea surface temperatures due to greenhouse gases requires measurements that average over periods long enough to distinguish the warming signal from the larger seasonal and decadal variability of naturally occurring phenomena, such as the El Niño and La Niña.[22]

Detection and attribution of climatic changes and long-term trends in the Earth system—addressing, for example, land cover and land use, storm intensity, ground water change, aerosols, ozone pollution and recovery, ice mass loss, and sea level change—require sustained measurements. Such measurements are also necessary to understand climate processes characterized by low-frequency variability. Because changes on a wide range of time and space scales affect Earth, each measurement's sampling characteristics need to be carefully designed to meet well-defined scientific and societal sampling objectives. Program plans for sustained measurements are based on current knowledge of the Earth system; however, they also must accommodate expanded understanding or unanticipated developments regarding climate and other global change. An observing system may very well reveal unexpected phenomena such as the Antarctic ozone hole, the depletion of subsurface aquifers, or the frequency/occurrence of natural, low-frequency events like El Niño and La Niña. Scientific opportunities are lost and the scientific basis for decision making eroded if the observing strategy cannot adapt accordingly. In addition to their scientific value, long-term observations (e.g., atmospheric carbon dioxide concentrations, sea level change, solar output) have become the focus of policy debates on anthropogenic contributions to global warming (Myhre et al., 2013). The especially stringent requirements for a climate-quality record of the Sun's total irradiance at Earth are discussed in a 2013 NRC report (NRC, 2013).

1.2 SCOPE OF THIS REPORT

The ad hoc committee formed in response to the NASA study request ("Statement of Task," Appendix A) was asked to develop a framework to assist NASA's ESD in their determinations of when a measurement(s) or data set(s) should be collected for durations longer than the typical lifetimes of single satellite missions. In particular, and considering the expected constrained budgets for the NASA Earth science program, the committee was asked to:

1. Provide working definitions of, and describe the roles for "continuity" for the measurements and data sets ESD initiates and uses to accomplish Earth system science objectives; and

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[21] The President's fiscal year 2016 budget, which was released on February 2, 2015, after a draft of this report had been submitted for external peer review, proposes to transfer responsibility for ocean altimetry missions following Jason-3 from NOAA to NASA. See page ES-37 in NASA, "FY 2016 President's Budget Request Summary," http://www.nasa.gov/sites/default/files/files/NASA_FY_2016_Budget_Estimates.pdf.

[22] On attribution, see Bindoff et al. (2013). On the need for a blend of short-term, focused measurements as well as systematic, long-term measurements, see NRC (2000).

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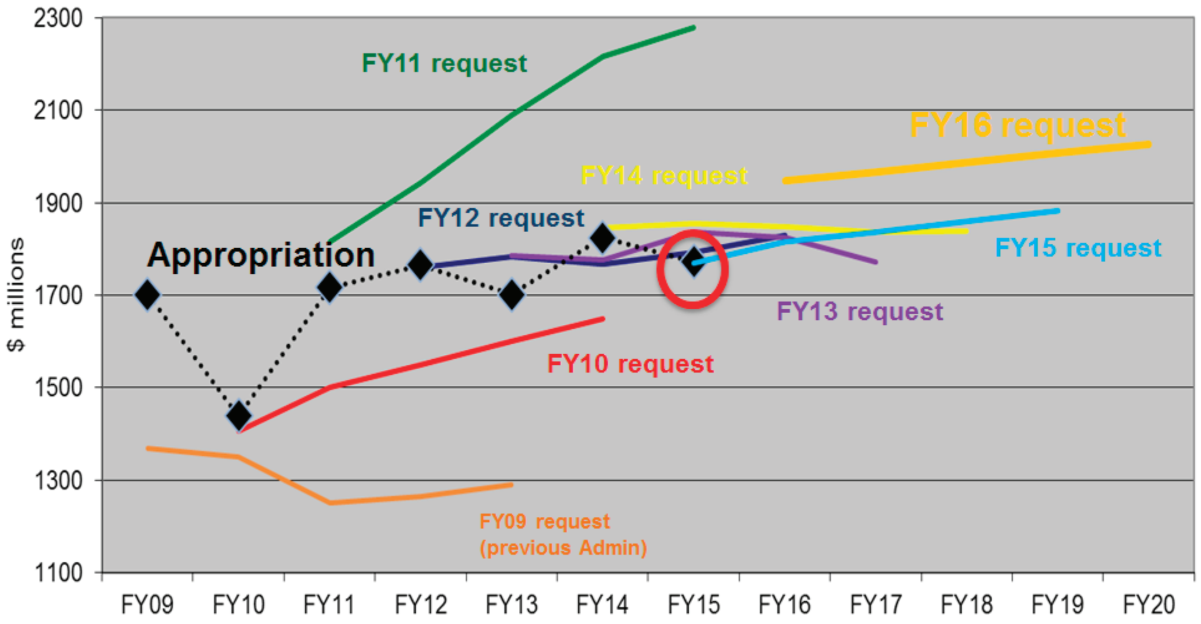
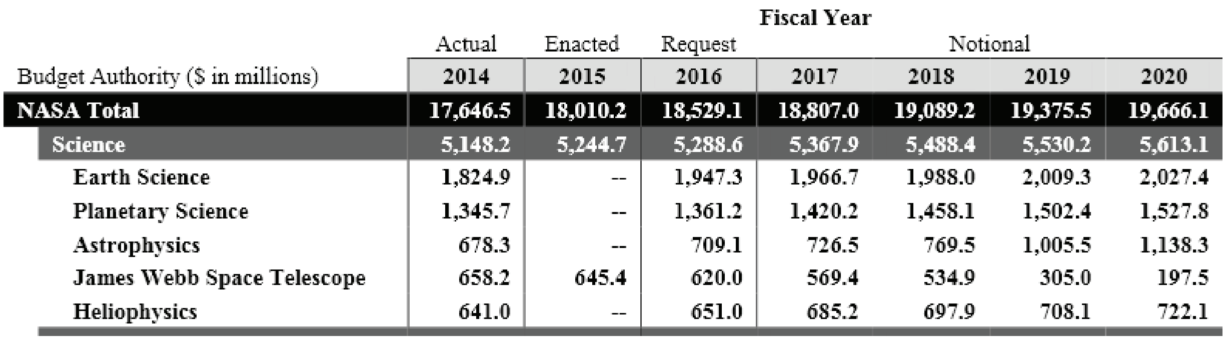


FIGURE 1.1 Earth science budget: fiscal year (FY) 2016 request/appropriation. SOURCE: Michael H. Freilich, NASA Headquarters, "NASA Earth Science Division: Status, Plans, Accomplishments," July 27, 2015, http://science.nasa.gov/media/medialibrary/2015/08/11/FREILICH_July_SC_ESD.pdf.

TABLE 1.1 NASA FY 2016 President's Budget Request Summary



	Fiscal Year						
	Actual	Enacted	Request	Notional			
Budget Authority ($ in millions)	2014	2015	2016	2017	2018	2019	2020
NASA Total	**17,646.5**	**18,010.2**	**18,529.1**	**18,807.0**	**19,089.2**	**19,375.5**	**19,666.1**
Science	**5,148.2**	**5,244.7**	**5,288.6**	**5,367.9**	**5,488.4**	**5,530.2**	**5,613.1**
Earth Science	1,824.9	--	1,947.3	1,966.7	1,988.0	2,009.3	2,027.4
Planetary Science	1,345.7	--	1,361.2	1,420.2	1,458.1	1,502.4	1,527.8
Astrophysics	678.3	--	709.1	726.5	769.5	1,005.5	1,138.3
James Webb Space Telescope	658.2	645.4	620.0	569.4	534.9	305.0	197.5
Heliophysics	641.0	--	651.0	685.2	697.9	708.1	722.1

NOTE: The enacted fiscal year 2015 funding for NASA Earth Science is $1,772.5 million. Appropriations for fiscal year 2016 were still pending as this report went to press; however, it is expected to be between the House's preferred $1,682.9 million and the Senate's preferred $1,931.6 million. (Updates to this table were received during editing.)
SOURCE: NASA, "FY 2016 President's Budget Request Summary," https://www.nasa.gov/sites/default/files/files/ NASA_FY_2016_Budget_Estimates.pdf, accessed September 23, 2016.

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2. Establish methodologies and/or metrics that can be used by NASA to inform strategic programmatic decisions regarding the scope and design of its observation and processing systems:
   a. In the context of limited resources and recognizing the programmatic and fiscal tension between the scientific benefits of providing sustained measurements on the one hand, and developing and demonstrating new or improved measurements on the other hand, determine whether a measurement(s) should be collected for extended periods, and provide guidance concerning methods to determine the appropriate balance between cost, risk, and performance when addressing continuity needs for specific measurements;
   b. Prioritize the relative importance of measurements that are to be collected for extended periods; and
   c. Identify the characteristics of, and extent to which, data gaps and/or accuracy/sampling/stability degradations are acceptable for existing and planned data sets.

In carrying out its task, the committee focused on providing a framework that would allow prioritization of measurements based on their scientific value. With respect to item 2 above, the committee's decision framework and examples (see Chapter 3) are most applicable to choices among extended missions undertaken for research purposes aimed at quantifying global change.[23] For such decisions, emphasis is on extending measurements to understand the signals of the Earth system under a changing climate and further to provide the observational basis for improved models and model projections of future climate impacts. With this specific focus, the recommended framework is intended as a new method for evaluating science-driven continuity missions and represents a complement to the existing NASA proposal evaluation processes for NASA Research Announcements[24] and Earth Venture Announcements of Opportunity.[25]

Extended missions directed primarily at operational- or applications-based needs did not readily lend themselves to the framework here that balances scientific needs to make choices; however, applications-based priorities could be amenable to a similar approach. The committee lacked the expertise in these other areas to be able to make a suitable framework.

The committee's quantitative framework is focused on known quantities, specifically the time series of Sun-Earth observations that have been made and used in scientific analyses. It allows an examination of the question of whether these observations to date provide information that warrants their continuation. With pertinent (different) quantified objectives in Earth science, a similar framework is equally applicable to establish priorities among new, first-of-a-kind measurements, as well as to examine operational- or applications-based measurements. Developed appropriately, the committee envisions a single comprehensive evaluation approach for both new and continuity measurements, driven by science and/or application objectives. Finally, an important practical limitation of frameworks like those presented here lies outside the science community: While the scientific priorities for future NASA science missions are guided by NRC decadal surveys, NASA also responds to congressional or executive branch input, which can result in important deviations from the scientific strategic plan.

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[23] A particular challenge in developing a metric to value the contributions of a particular measurement/observation to an application objective is the diversity of applications, which range from low-frequency, high-impact, and localized events (monitoring crustal movements of Earth to better predict mudslides, volcano eruptions, and earthquakes) to observations of the long-term, global-scale effects of climate change (monitoring sea surface height, global mass redistribution, ice sheet dynamics, temperatures and precipitation). As discussed in this report, even prioritization of the scientific value of the more "apples-to-apples" comparisons of the latter group of climate observations is extremely challenging.

[24] See Appendix C, "Proposal Processing, Review, and Selection," in *Guidebook for Proposers Responding to NASA Research Announcement (NRA) or Cooperative Agreement Notice (CAN)*, January 2015, http://www.hq.nasa.gov/office/procurement/nraguidebook/proposer2015.pdf.

[25] See Section 7.0, "Proposal Evaluation, Selection, and Implementation," in *Draft Announcement of Opportunity, Earth Venture Mission – 2, Earth System Science Pathfinder Program*, Solicitation Number NNH15ZDA008J, May 12, 2015, http://nspires.nasaprs.com/external/.

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2

Measurement Continuity

2.1 CONTEXT

By the late 1980s, the scientific disciplines that had for the most part independently studied Earth's atmosphere, oceans, land, cryosphere, and ecology recognized the need to conceptualize Earth as an interactive set of systems, affected both by human activities and natural changes. These processes and their interactions, illustrated by the "Bretherton diagram" (NAC, 1986) in a set of reports led by geophysical fluid dynamicist Francis P. Bretherton, elucidated the concept of Earth system science.[1] The mid- to late-1980s were also the period when, as part of its contribution to a multiagency response to the challenge of understanding Earth as an integrated system of interacting components, NASA initiated the Earth Observing System (EOS) program.[2] The EOS program culminated in the launch of its flagship Terra, Aqua, and Aura facility-class spacecraft in 1999, 2002, and 2004, respectively.[3] Since then, a set of Earth System Science Pathfinder[4] and Earth Systematic Missions[5] have also been successfully launched including Aquarius, CALIPSO, CloudSat, GRACE, OCO-2, SMAP,[6] the Jason series of ocean surface topography satellites; and GPM. Two other spacecraft—GLORY and OCO—were completed but lost due to launch failures.

The first Earth science and applications from space decadal survey (NRC, 2007), initiated in 2005, was organized thematically, dividing Earth system science into the following topics: weather science and applications; climate variability and change; land-use change, ecosystem dynamics, and biodiversity; water resources and the global hydrologic cycle; solid-Earth hazards, natural resources, and dynamics; and human health and security. Study panels in each of these areas prioritized candidate missions that would address new or continuing mea-

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[1] Excerpted from CIESIN (2013).

[2] First person accounts of the history of the EOS program may be found in NASA (2008).

[3] Also launched during this period with funding from the EOS program were ICESat, Landsat 7, QuikScat (Quick Scatterometer), ACRIMSat (Active Cavity Radiometer Irradiance Monitor Satellite), Jason-1, SAGE III (Stratospheric Aerosol and Gas Experiment-III), and SORCE (Solar Radiation and Climate Experiment).

[4] The ESSP program also encompasses NASA's Earth Science Division's NASA's Earth Venture (EV) class of missions: a series of uncoupled, relatively low-to-moderate cost, small to medium-sized, competitively selected, full orbital missions (EVM), instruments for orbital missions of opportunity (EVI) and suborbital projects (EVS), legacy ESSP Projects. See NASA (2015).

[5] NASA "Earth Systematic Missions," http://science.nasa.gov/about-us/smd-programs/earth-systematic-missions, accessed April 6, 2015.

[6] SMAP (Soil Moisture Active-Passive) is the successor to the ESSP Hydros (Hydrosphere State) mission, which was cancelled by NASA due to budget constraints in late 2005.

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surement needs; however, a satisfactory scheme to value candidate missions/measurements across these themes was not established.[7] The next decadal survey in Earth science and applications from space, which is scheduled to begin in 2015, will confront this problem anew, exacerbated by the increasing number of measurements that are candidates for continuation and the large number of missions remaining in the queue of the previous decadal survey. Figure 2.1 illustrates the scale of the problem; it shows NASA Earth Science Division (ESD) missions currently in operation or in an advanced stage of planning. Table 2.1 shows ESD missions that might be in operation over the next 20 years.

The current and potential future NASA missions respond to the challenge of understanding the integrated Earth system globally in the pursuit of knowledge to address pressing societal needs—for example, weather and climate prediction; climate change impacts; the health of ecosystems; adaptation and protection from natural hazards. In general, they are also aligned with the Administration's overarching emphasis on climate research and monitoring while being consistent with and informed by the 2007 NRC decadal survey.

While recognizing the preeminent importance of climate science in NASA's Earth science programs,[8] the committee also appreciates that ESD programs are shaped by consideration of a wide range of measurements for societal benefit, directly and indirectly, through increased scientific knowledge aiding projections made with Earth system models. Thus, the committee's analysis framework considers the requirement for suites of observations that will be assimilated into Earth system models for assessing the threats to society from climate change and the projection of key processes affecting society in the future. Addressing this challenge requires identifying the key components of the Earth system that affect a particular process (e.g., sea level rise, water balance, carbon cycle, etc.) and maintaining a "system science" approach (e.g., how do these measurements improve the overall projections).

The task of the present study focuses on evaluating the benefit of continued measurements after an initial implementation and analysis. It is presumed that the measurement period is beyond a single mission; therefore, in a capped budget environment, its continuation is at the expense of alternative competing missions and measurements. In developing a decision framework suitable to value competing choices in a tightly constrained fiscal environment, the committee began with the following questions:

- What are the quantifiable science objectives that are important and amenable to study with the synergy of the various existing measurements and models?
- What are the needs for, and definitions of, continuity with respect to each measurement and with respect to understanding global change?
- What are the temporal, spatial, and accuracy requirements for such measurements, whether they be current or proposed?
- Are there alternate approaches to meeting the measurement requirements with acceptable performance and/or reduced costs?

The answers to these questions provide a basis for prioritization across candidate continuity measurements and a framework and rationale for development of new measurement techniques. In the rest of this chapter, the committee provides its definition of continuity, including defining those aspects of a measurement that are important for continuity. The framework itself is presented in Chapter 3.

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[7] Each panel first set priorities among an array of space-based measurement approaches and mission concepts by applying the criteria shown in Chapter 2 of NRC (2007). Recommendations in previous community-based reports, such as those of the World Meteorological Organization, were also considered. The complete set of high-priority observations and missions identified by the panels numbered about 35, a substantial reduction from the more than 100 possible missions suggested in the responses to a broadly distributed "request for information," but more than a factor of two beyond what could be accommodated even with the assumed budget that grew by more than $5 billion during the decadal survey interval. Prioritizing across the panels was the responsibility of the steering committee of the decadal survey, which referred to criteria similar to that employed by the panels; the steering committee prioritization was also informed by a separate study panel, the Panel on Earth Science Applications and Societal Benefits.

[8] "The Obama Administration is acting on its recognition that climate change is a defining issue of our generation. Our responses to the challenges of climate change—accurate prediction, equitable adaptation, and efficient mitigation—will influence the quality of life for the nation, and indeed the world, for generations to come" (NASA, 2010, p. 2).

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FIGURE 2.1 NASA Earth Science Division Missions and Instruments as of September 2015. NOTE: This figure reflects the following recent developments: the Tropical Rainfall Measuring Mission (TRMM), launched on November 27, 1997, stopped data collection on April 8, 2015, after the spacecraft depleted its fuel reserves and began a descent into Earth's atmosphere that ended destructively on June 15, 2015; Aquarius launched on June 10, 2011, ceased operations on June 8, 2015, following a hardware component failure that resulted in a loss of onboard power regulation and spacecraft attitude stabilization; the radar on SMAP (Soil Moisture Active-Passive) stopped transmitting on July 7, 2015, due to an anomaly involving its high-power amplifier, although its radiometer continues to operate normally. SOURCE: Image courtesy of NASA Goddard Space Flight Center.

2.2 CONTINUITY: A WORKING DEFINITION

Scientific understanding of global change requires long-term, reliable measurements of the key physical variables that define the variability and shifts in state of the Earth system and its multiple components (see Box 2.1 for the committee's definition of measurement and several other terms used in this report). Without such observations of the climate system, predictions of the complex responses of the Earth system to human activities and natural variations lack the certainty needed to plan and prepare for climate change.

For any particular climate system variable, the requirements for the duration of an observing record can be determined if there is an adequate understanding of the expected natural variability and its coupling with other forced components of global change. Unfortunately, these aspects of the climate system are often uncertain until a long-term, continuous record is acquired.

For some variables, NASA pursues the construction of climate-quality records from requisite measurements made from the vantage point of space. For example, instruments placed on satellites in appropriate orbits measure total solar irradiance, ozone (total column and vertical profile) and global temperatures in the lower atmosphere—with attention to issues of calibration (and bias) uncertainty and repeatability—enabling the development of consistent, global time-series at appropriate spatial and temporal scales not otherwise available. For other variables,

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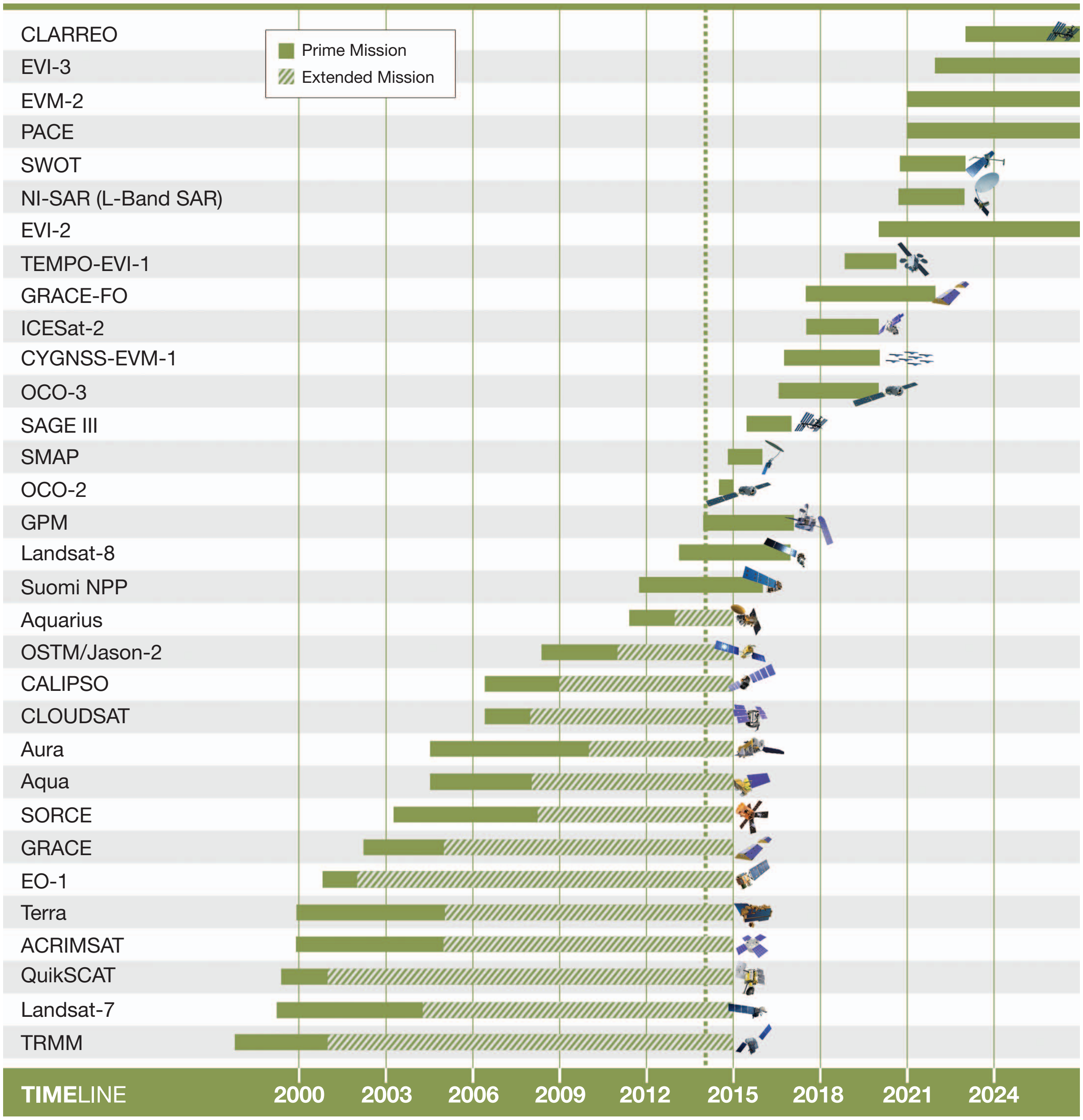
TABLE 2.1 Future NASA Earth Science Missions (as of 2014)



NOTE: The Tropical Rainfall Measuring Mission (TRMM) and Aquarius ceased operations in April and June of 2015, respectively. The extended missions depicted in Table 2.1 are approved for continued operations based on a senior peer review conducted by scientists every 2 years to determine the scientific value and priority of further mission extensions. Not shown are mid-2014 selections in the Venture-class: GEDI (Global Ecosystem Dynamics Investigation) and ECOSTRESS (Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station). See "NASA Selects Instruments to Track Climate Impact on Vegetation," press release, July 30, 2014, http://www.nasa.gov/press/2014/july/nasa-selects-instruments-to-track-climate-impact-on-vegetation/#.VUOqG_lVhBc.
SOURCE: NASA (2014).

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BOX 2.1
Definition of Terms

This report uses a number of relatively common Earth science terms whose meaning is context-dependent. For clarity, the committee adopts definitions similar to those of the World Meteorological Organization (WMO) Committee on Earth Observing Satellites (CEOS) (i.e., Definitions and Requirements from the WMO/CEOS database–2009 draft[1]), but modified to be consistent with NASA's Data Processing Level descriptions. Definitions of the terms used in this report are as follows:

- *Geophysical phenomenon.* A natural event or scene involving one or more geophysical variables.
- *Geophysical variable.* One of a set of measurable factors that define a geophysical phenomenon and determine its behavior. In this report, it is equivalent to the term "Geophysical Parameter." Note: "Essential Climate Variables" (ECVs; see footnote 11) represent a subset of Earth system geophysical variables.
- *Measurement.* A quantitative record of a geophysical variable obtained by appropriate processing and comparison to standards of instrumental observations of geophysical phenomena. In this report a measurement is equivalent to the phrase "derived geophysical variable" used in the NASA Data Processing Level Descriptions (Level 2).
- *Instrument.* A device with suitable characteristics for deriving a geophysical variable measurement from observations of geophysical phenomena. In this report the data record from an instrument is equivalent to the term "Instrument Data" used in the NASA Data Processing Level Descriptions (Level 1).

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[1] World Meteorological Organization (WMO) Committee on Earth Observing Satellites (CEOS), "Definitions and requirements from the WMO/CEOS Database - Draft, 13 October 2009," http://portal.opengeospatial.org/files/?artifact_id=38204.

like the evolution of well-mixed greenhouse gases, surface-based measurements may provide sufficient data. For highly heterogeneous phenomena such as the effects of tropospheric aerosols on climate, satellites are needed to provide the necessary global maps and integrated impacts. Successful support of climate applications from satellites requires a strategy to provide for the essential characterization of the measurements: instrument calibration uncertainty, repeatability, time and space sampling, and data systems and delivery for climate variables (algorithms, reprocessing,[9] and availability).

Many geophysical variables related to societal needs and goals vary naturally on long time scales (decades to centuries) and all spatial scales. The differences between human-forced changes and natural variability are difficult to detect until the former emerge above the natural variability of the climate system, usually after a decade or more of measurements (Bindoff et al., 2013). A current example is the slowdown ("hiatus") in global mean surface warming over the past 15 years (Flato et al., 2013, Box 9.2). Detecting small, gradual changes requires well-calibrated, stable measurements made over long periods. Whether from remote sensing or in situ observations, it has proven extremely difficult to satisfy these measurement requirements over the decades necessary to resolve low-frequency variability in Earth's environment. Subtle shifts in instrument calibration and performance and changes in processing can be mistaken for natural variability or anthropogenic change in the Earth system. Thus, it is necessary to maintain the ability to carry forward the science information essential to reconstruct a consistent time series of a geophysical variable from various instrument data sets. Reprocessing of instrument data acquired in the past is typically a necessary component for developing consistent climatological time series.

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[9] For more on reprocessing and reanalysis, see Bosilovich et al. (2013).

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Ensuring continuity of a geophysical variable from a sequence of "improved" instruments, or from copies of the same instrument, requires a careful program of instrument calibration, characterization, cross-comparison, and validation. Satellite instruments present particularly difficult challenges for the development of long-term, well-calibrated time series at any spatial scale because once on orbit they are no longer amenable to regular, repeated laboratory calibration and characterization. In operational programs, copies of instruments have been flown multiple times with the goal of simplifying this process. Although copies do not eliminate the need for calibration, characterization cross-comparisons, and validation, such an approach—including strategic group procurements of instruments or spacecraft—can reduce costs and typically reduce the risk in providing a long-term continuous record.

In addition to the basic instrument measurement, an adequate total observing system comprises platform orbital characteristics, instrument calibration tracking, data-processing algorithms, auxiliary data sets, and numerical models to derive geophysical data products. Changes in platform observing characteristics (altitude, orbit crossing times, etc.) introduce perturbations into the entire system. Development of calibration methods through satellite mission overlaps and surface-based overlapping measurements directly traceable to the National Institute of Standards and Technology (NIST) or other standards is necessary to provide reliable long-term measurements of geophysical variables.

In summary, the generation of a high-quality data set requires measurements made by well-characterized, calibrated, and stable instruments, validated algorithms, and consistent auxiliary data. In turn, this requires an assessment of instrument uncertainty and repeatability, temporal and spatial sampling, consistent algorithms, and provision for data reprocessing. With this in mind, the committee finds that the following is a sufficient high-level definition of continuity across the Earth science subdisciplines for use in an analysis framework focused on scientific objectives:

Finding: Continuity of an Earth measurement exists when the quality of the measurement for a specific quantified science objective is maintained over the required temporal and spatial domain set by the objective. The quality of a measurement is characterized by its combined standard uncertainty, which includes instrument calibration uncertainty, repeatability, time and space sampling, and data systems and delivery for climate variables (algorithms, reprocessing, and availability)—each of which depends on the scientific objective.

The committee identifies below four criteria—instrument calibration uncertainty, repeatability, continuity, and data systems and delivery—necessary for determining whether a data set has the requisite quality for long-term Earth observations and global change research. These criteria are fundamental to the framework introduced in Chapter 3 associated with the "quality" characteristic.

2.2.1 Instrument Calibration Uncertainty

To achieve a long-term record of a climate variable with acceptable uncertainty for use in Earth system science, it is essential to calibrate the instrument before flight, monitor the calibration changes in orbit, and, in many cases, cross-calibrate and monitor similar, but not necessarily identical, instruments. The uncertainty requirement for the measurement of a particular variable is determined by the variable's signal magnitude, the expected temporal and spatial variability, and the requirements of the quantified science objective.

It is extremely difficult to calibrate an instrument to make measurements with sufficiently small uncertainty that climate change detection is possible without overlap to remove calibration bias. Instrument calibration methodology must be consistent across multiple instruments. An ongoing commitment to on-orbit calibration and characterization is essential in a continuity mission to assess the stability (or not) of the initial calibration. By providing instrument cross-calibration and in-flight calibration tracking validation, Earth observation data from NASA and national and international partners complement and add to the observations provided by other systems. As these data records are extended, merging them with retrospective data acquired by earlier satellites leverages their utility for climate change studies, but typically requires additional reprocessing as new measurements elucidate new understanding of the behavior of the instruments that acquired the earlier measurements.

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A lack of careful and comprehensive calibration—with attendant large measurement uncertainty—substantially limits the value of the merged long-term data record, and decreases its value to the scientific enterprise. Detecting and characterizing change in relevant Earth system properties by comparing data from different instruments becomes difficult, if not impossible. Examples can be found in such basic measurements as the energy output of the sun, sea surface temperatures, total ozone columns, the global cloud cover and energy balance, and sea level changes. Good-practice approaches to instrument calibration that incorporate NIST-traceability are necessary to prevent incorrect scientific inferences from comparisons and analyses of measurements whose disparate uncertainties render them incompatible.

Historically, space-borne Earth observation instruments have been designed to achieve the necessary sensitivity and resolution for studying rapidly changing Earth processes and relatively fine spatial and temporal scales, such as weather systems. When considering program costs, absolute calibration of these instruments was a secondary consideration to their sensitivity. Recently, there has been an increased focus on the use of space-based global observations to understand climate change. However, major radiometric calibration challenges exist for instruments measuring, for example, atmospheric temperature (microwave and infrared sounders), cloud properties (reflected solar and infrared imaging radiometers), radiation budget (broadband scanning radiometers), ozone (back-scattered ultraviolet radiometer), and other geophysical variables that are key indicators of climate and global change (Myhre et al., 2013; NRC, 2007).

In lieu of the calibration uncertainty needed to detect climate change without overlapping measurements, most instruments in orbit attempt to use overlapping observations to cross-calibrate successive instruments with each other and then attempt to estimate instrument calibration stability over its lifetime (see Box 2.2 for an example for total solar irradiance observations). But constraints on stability for most instruments remain problematic. Over instrument lifetimes of 5-10 years on orbit, drifts in measurement bias occur due to contamination and degradation of materials in orbit (NRC, 2013; Loeb et al., 2007). The challenge is especially severe for reflected solar radiometers where calibration changes can reach 3 to 5 percent of the mean signal over the instrument lifetime—changes that are larger than the decadal climate change of interest.

BOX 2.2
Radiometric Uncertainty

Methods for constructing rigorous requirements have been developed for climate change observations (e.g., Leroy et al., 2008; Wielicki et al., 2013; NRC, 2013). For example, in the context of key science questions on cloud feedback with global warming, the reflected solar energy has a required uncertainty of 0.3 percent relative to laboratory standard of the reflected solar radiation (95% confidence). In the context of surface temperature trends, the required uncertainty is 0.07 K in brightness temperature (95% confidence). These uncertainties are a factor of 5 to 10 more stringent than typical for current Earth observations from reflected solar and infrared radiometers. Further detail of these methods can be found in Section 4.3 and Appendix C (e.g., Figure C.1).

This challenge was recognized by the first Earth science decadal survey (NRC, 2007), which proposed a mission called CLARREO (Climate Absolute Radiance and Refractivity Observatory) to serve as an in orbit National Institute of Standards and Technology-traceable set of spectrometers covering the entire reflected solar and thermal infrared. These spectrometers would provide an orbiting cross-calibration standard for 30 to 40 Earth-viewing instruments covering radiation, temperature/humidity profiles, sea surface temperature, cloud properties, aerosols, land processes, and ocean biosphere measures. The CLARREO mission remains under study, but represents a new way to bring a host of struggling earth science records up to future climate quality. Recent international studies (Goldberg et al., 2011; Dowell et al., 2013) have recommended such a system in orbit. Having on-orbit, long-term cross-calibration for the range of active satellites measuring the radiation budget would allow rigorous determination of instrument calibration drifts as well as allow crossing instrument gaps without inducing large uncertainty in climate change records.

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Thus, critical questions are the following: What calibration uncertainty is required for the specific climate change objective being investigated? What is the point of diminishing returns? How do we decide if a measurement needs to be continued as is (with or without overlap), or needs improved accuracy for climate change? Box 2.2 provides an example of constructing requirements for radiometric uncertainty. Further examples in Chapter 4 and the appendixes demonstrate methods to quantify the different levels of accuracy achieved with and without continuity of observations.

2.2.2 Repeatability

The detection of trends in climate variables in the presence of real temporal and spatial variability requires observations with acceptable calibration uncertainty and repeatability over a long period of time. Acquiring a multi-decadal record is generally beyond the scope of a single satellite-instrument mission, thereby requiring multiple launches of space-qualified instruments. To answer climate change questions, these longer-term records are important for separating trends in the presence of larger seasonal and decadal variations. In general, there is a requirement for near-continuous observations without significant breaks that might miss the variability or step-trend that needs to be characterized. The sampling interval, as well as whether there can be an acceptable break in the measurement, depends on the relative magnitudes of the seasonal, decadal, and trend components of the signal. In the case in which there are diurnal variations due to clouds or diurnal heating of the surface, for example, the replacement sensors should observe at nearly the same time (if sun-synchronous) to avoid aliasing diurnal variations into other temporal changes.

Even with overlapping observations, it is still difficult to achieve climate change detection unless the repeatability of the measurement is sufficiently high. Repeatability relates to the consistency of time series of measurements of a given geophysical phenomena with the same or similar instruments. Repeatable measurements may not be accurate; for example, as a result of systematic error, or bias, that may be poorly known, or as a consequence of the random error, or noise,[10] in a measurement that cannot be fully accounted for, but an accurate measurement (i.e., one with small uncertainty) will be repeatable. If the instrument lacks precision (i.e., repeatability on short time scales) the resultant noise can affect long-term repeatability. For example, the acquisition of reliable climate variables with acceptable repeatability (e.g., a factor of 10 less than its expected, forced change) leads to a critical need to perform intra-system and inter-system comparisons of individual measurements made for global change research, monitoring, and attribution. This strategy may require at least two similar or identical instruments to be in orbit at the same time, although not necessarily in the same orbit or observing the Earth system at the same time.

For many space-based instruments, however, demonstration of repeatability will require observations matched in time, space, and satellite viewing angle. The Global Space-based Intercalibration System (GSICS) provides an extensive literature of such studies (Goldberg et al., 2011). Instrument overlap enables comparisons of the calibration, performance, and idiosyncratic characteristics of different observing systems, knowledge of which is crucial for establishing the degree of measurement repeatability.[11] In some cases, ground or suborbital observations may be able to provide a measure of calibration consistency (albeit with larger uncertainty) across multiple satellite instruments. Or it may be that overlap of similar instruments is required to achieve the needed repeatability (Box 2.3)—this leads to the requirement that a follow-on instrument be launched before, not after, the failure of the replaced instrument.

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[10] Noise is often distinguished from bias by requiring that it refer to errors that have a zero mean value.

[11] Relying on measurement repeatability alone to achieve the needed long-term climate observations requires that instrument overlap be assured and the overlapping data record be rigorously compared. To date, the primary example of this is the record for total solar irradiance. Many other climate records struggle with either high probability of overlap (radiation budget from ERBE (Earth Radiation Budget Experiment) to CERES (Clouds and Earth's Radiant Energy System), for example) or rigorous demonstration of stability (for example against international standards). The 33-year multisatellite altimeter data record, which was initiated by the TOPEX/Poseidon mission, is an example where these considerations are important. The committee's proposed framework is sufficiently flexible to consider both options because both quality and success probability are quantitatively considered. If repeatability can be demonstrated, and is required to attain the quality metric, then the success probability metric can be used to assess the likelihood that the proposed observing system will achieve overlap.

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BOX 2.3
Repeatability of Total Solar Irradiance Measurements

The Sun is the primary energy source for Earth, and changes in solar irradiance force changes in climate. Once considered constant, total solar irradiance (TSI) is now known to vary continuously with solar activity. Measurements made by space-based solar radiometers have recorded increases of 0.1 percent from the minimum to the maximum of the Sun's 11-year activity cycle. Historical proxy indicators of solar activity indicate that changes in TSI, averaged over the solar cycle, may exceed those within the 11-year cycle—that is, TSI changes larger than 0.1 percent may be possible on multi-decadal to century time scales.

The requirement for the solar irradiance climate record is that the measurements have the repeatability to detect a change in TSI over 50 years to within 0.75 W m^{-2} (NRC, 2013, Box 2.2). The absolute value of TSI during solar minimum is 1360.8 W m^{-2}, so the corresponding climate requirement is a repeatability of 0.01 percent (100 ppm) per decade.[1] Comparison of different TSI measurements made by individual space-based radiometric instruments during the 35-year record indicates uncertainties in the range 2 to 4 W m^{-2} (0.1-0.3 percent). Because the absolute calibration uncertainties of these measurements exceed the repeatability requirement (by more than a factor of two) it is not possible to achieve a solar irradiance climate record with the needed repeatability without cross-calibration of the radiometric scales of individual solar instruments. Securing this cross calibration requires overlap of the individual measurements.

By virtue of in-flight sensitivity tracking, for example with redundant radiometric cavities having different duty cycles, the repeatability of individual TSI measurements significantly exceeds the uncertainties. Comparisons of drifts among independent measurements during periods of overlap during the 35-year record suggest repeatability that are of order 15 ppm per year but can reach 40 ppm per year. Composite records constructed by cross calibrating individual measurements suggest that the extant 35-year TSI climate record has a repeatability of order 100 ppm per decade, determined as the drift between two independent composite records from 1979 to 2013 (Figure 2.3.1).

The TSI record in the most recent decade is more certain and has higher repeatability than does the record of the prior two decades. This is because of the deployment of the newly designed, characterized, and calibrated state-of-the-art Total Irradiance Monitor (TIM) on the Solar Radiation and Climate Experiment (SORCE) spacecraft. TIM has a repeatability of 11 ppm per year and a calibration uncertainty of 300 ppm. By applying the characterization and calibration techniques to a copy of a flight radiometer, a revised absolute scale has been determined for the ACRIMSat (Active Cavity Radiometer Irradiance Monitor Satellite) radiometer measurements, which now agrees with TIM to within 0.3 W m^{-2} (220 ppm). The overlapping observations thus provide the repeatability requirement for the solar irradiance climate record.

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[1] The comparison of any two measurements at any particular time—needed to cross calibrate multiple measurements that compose the climate record—relies on their absolute calibrations at the time of comparison, which is a combination (in the sense of combined standard uncertainty) of their NIST-traceable absolute calibration and the repeatability of that calibration with time. The time-dependent factor (relative calibration, or repeatability) is measured per unit time, since this defines the acceptable drift in the absolute calibration that still enables meeting the quantified objective for the climate (i.e., TSI in this case) record. So, for example, the comparison of two different measurements made by a sensor just launched and a sensor that has been operating for a decade will have an uncertainty not just because of their respective absolute calibrations at launch, but also because of drifts over 10 years of operation, and this is the value that is given for TSI repeatability.

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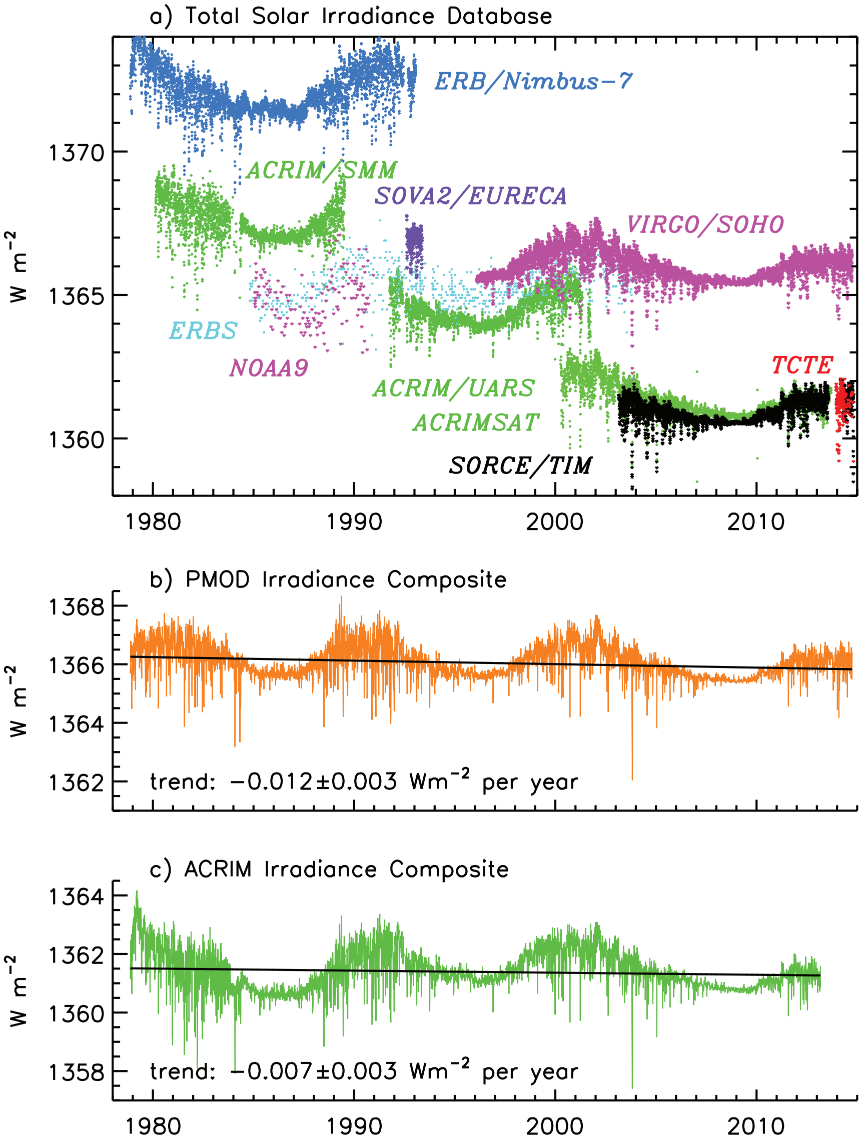

FIGURE 2.3.1 Spaceborne measurements of total solar irradiance (TSI) are shown on their "native" scales with offsets attributable to calibration errors. Instrument overlap allows the cross calibration of the offsets and the creation of composite TSI records This is possible because the TSI measuremenrs are sufficiently repeatable that true solar irradiance variations are detectable. Thus, individual TSI observations are all larger during times of higher solar activity (e.g., around 1990 and 2000). Also shown are two composite records of TSI, constructed using different assumptions about the calibration biases and drifts of individual measurements, and with different adopted absolute irradiance scales. Even with the cross-calibration achieved from instrument overlap, true multi-decadal solar change is arguably not yet detectable in the long-term TSI record because of insufficient long-term repeatability of most of the extant measurements. For this reason the two different composite records exhibit different long-term trends in addition to having different absolute scales; they are used to illustrate the value framework in Appendix B. To detect true TSI changes without instrument overlap requires absolute calibration with uncertainties an order of magnitude smaller than that of most of the observations shown in this figure. SOURCE: Adapted from Figure 1 of G. Kopp and J.L. Lean, 2011, A new, lower value of total solar irradiance: Evidence and climate significance, *Geophysical Research Letters* 38:L01706.

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2.2.3 Time and Space Sampling

The quality of a geophysical data set also depends on its time and space sampling. For satellite observations, this sampling is determined by a combination of instrument design and satellite orbit. For suborbital observations (e.g., IceBridge) it is determined by instrument, airborne platforms, flight schedules, and flight tracks. Attempts to retrieve a long-term data set of a climate variable with an underlying cyclic or chaotic variation (e.g., diurnal or seasonal temperature variation, weather patterns) must take into account the time and space sampling of the satellite orbit.

Many geophysical variables (e.g., clouds and precipitation, sea level, biomass burning, tropospheric ozone) have significant temporal variation that may be both chaotic (weather systems) and systematic (diurnal or seasonal). For chaotic variability it is advantageous to have as many measurements as possible; but for systematic variability, it is critical to avoid a biased sampling of the diurnal or seasonal cycles typical with low Earth polar orbits (e.g., by flying dual instruments with one sun-synchronous and the other precessing). To achieve a measurement strategy for highly variable global systems such as clouds and precipitation, NASA ESD and its partnering national and international space programs include multiple sun-synchronous satellites in orbit at different times of the diurnal cycle, or sometimes single spacecraft that are in mid-inclination with orbits that precess through all local times of day. A high-temporal-repeat sampling strategy is also important for severe weather prediction, such as hurricanes, floods, lightning, and tornadoes, and is a primary focus of geosynchronous observing systems.

Time and space sampling is also relevant to intercalibration of overlapping sensors as discussed above in the section "Repeatability." This may be illustrated by an analysis of the reduced uncertainty caused by changing the diurnal sampling time. EarthCare is an upcoming European Space Agency mission[12] to make global observations of clouds, aerosols and radiation; its payload includes a high-resolution cloud and aerosol vertical profile lidar. CALIPSO,[13] a spacecraft developed cooperatively by NASA and the Centre National d'Études Spaciales (CNES, the French space agency), makes observations from a 1330LT (1:30 pm, local time) ascending sun-synchronous orbit. However, EarthCARE is 1400LT, roughly 30 minutes later, which adds to uncertainty in climate trends of cloud properties because of the systematic time difference in regions with large cloud diurnal cycles. However, this type of uncertainty can be estimated from observations (geostationary satellites, surface lidar network, surface cloud observations) and used in determining the quality level for a changed orbit crossing time continuity observation. The effect of this change will vary with cloud type (marine boundary layer vs land convection) and spatial scale (regional, zonal, global). For aerosols, the diurnal cycle is much smaller but the same analysis will be required. In some cases, models can also be used to assess such an uncertainty depending on model fidelity for the diurnal cycle of interest.

Time and space sampling influences both the ability to resolve spatial and temporal features as well as the uncertainty with which they can be observed at a given time and space scale. Changing spatial resolution between instruments can lead to the need to spatially average new higher resolution observations to provide continuity with existing lower spatial resolution instruments. Time sampling shifts occur when: (1) there is a change in the local equator crossing time for a sun-synchronous satellite, either by design or through uncontrolled drift, (2) there is a change in satellite altitude, thereby altering the ground repeat cycle of images, or (3) there is a change in the longitude of a geostationary satellite or a change in the sampling rate of an on-board instrument. The derivation of long-term, multi-satellite atmospheric temperature trends from satellite microwave measurements is a prime example of where drifts in satellite altitude and local measurement times have significantly complicated the task. Corrections for local measurement time are one of the main sources of uncertainty in current climate-quality data sets from these microwave sounders (Box 2.4).

The meaning of gaps in time and space sampling can be confusing. All data sets have time and space gaps and/or smoothing. For measurements made by instruments on space-based platforms gaps are typically one of two types. The first, "Type 1," is by design and is associated with orbit and instrument characteristics. For example, Landsat 8 orbits Earth once every 99 minutes at an average altitude of 438 miles (705 kilometers), repeating the

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[12] For an overview of the EarthCare mission, see ESA (2011).

[13] In 2006, NASA launched the CloudSat and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) spacecraft to study the role that clouds and aerosols play in regulating Earth's weather, climate, and air quality. See the CALIPSO mission homepage at http://www.nasa.gov/mission_pages/ calipso/mission/.

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same ground track every 16 days. “Type 2” gaps are unplanned gaps, usually related to instrument or spacecraft anomalies that either corrupt or eliminate an observation for a time period longer than Type 1 gaps.

This report does not define continuity of a measurement as a simple continuous time series of Type 1 gaps while avoiding all Type 2 gaps. Instead, measurement continuity pertains to maintaining the quality of the geophysical measurement, at the level needed to accomplish the quantified objective (see Section 3.1.1). This approach provides a robust, quantitative, and flexible definition for the quality of a measurement. Since quality relates to the combined standard uncertainty of the measurement, achieving the required quality can be accomplished with a wide range of potential combinations of instrument accuracy, repeatability, time/space sampling, algorithm and modeling uncertainty. Some instruments can be spaceborne while others can be surface or aircraft instruments. For example, a recent attempt to increase the quality of ice sheet elevation observation made by the short-lived ICESat satellite used aircraft lidar and radar observations in a program called IceBridge: these observations were designed to bridge the Type 2 gap between ICESat and ICESat 2 (Qi and Braun, 2013; Studinger et al., 2010).

BOX 2.4
Orbital Maintenance of Altitude and Time Sampling

Detection of climate change over a decade in atmospheric layers requires temperature to be measured to within an uncertainty of 0.2°C with a repeatability of 0.02°C (GCOS, 2010). This uncertainty and repeatability is needed to detect trends and variability in the troposphere and stratosphere temperature at global and regional scales, and to validate climate model predictions.

Atmospheric temperature has been measured from space since 1978 by microwave sounder instruments (Microwave Sounding Unit [MSU], Advanced Microwave Sounding Unit [AMSU], and Advanced Technology Microwave Sounder [ATMS]) carried on a series of National Oceanic and Atmospheric Administration, NASA, and EUMETSAT (European Organization for the Exploitation of Meteorological Satellites) satellites.[1] Microwave sounders measure radiance emitted from the surface and atmosphere at specific frequencies. These radiance measurements are used, along with atmospheric weighting functions, to determine the mean temperature of thick layers of the atmosphere. Lower tropospheric temperature (TLT) retrievals are dependent on the difference between nadir and near-limb views and thus are especially sensitive to changes in Earth incidence angle. Drag caused by the upper atmosphere results in a slow decay in orbital altitude of a satellite throughout its mission, which changes Earth’s incidence angle and can produce a spurious decreasing trend in lower tropospheric temperature retrievals. Once the changes in Earth incidence angle are accounted for, the warming trend in these temperatures more closely matched surface measurements and modeled trends (Wentz and Schabel, 2000).

Additionally, diurnal variations in temperature may be aliased into the long-term temperature trend (Figure 2.4.1). There was an error in an early method developed to estimate and remove the effects of changing diurnal sampling (Christy et al., 2003). More recent methods use hourly output from general circulation models to simulate the diurnal cycle in radiance for each satellite view angle and channel, allowing the effects of diurnal sampling to be removed. (Mears and Wentz, 2005, 2009). These newer methods from the Remote Sensing System (RSS) still result in different trends (Figure 2.4.2) that compromise the quality of the temperature records; these records provide examples in Appendix B to illustrate the framework application.

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[1] These measurements have been found to have many errors over time, highlighting the essential role of reprocessing in the generation of climate data records. See Bosilovich et al. (2011) and Abraham et al. (2014).

continued

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BOX 2.4 Continued

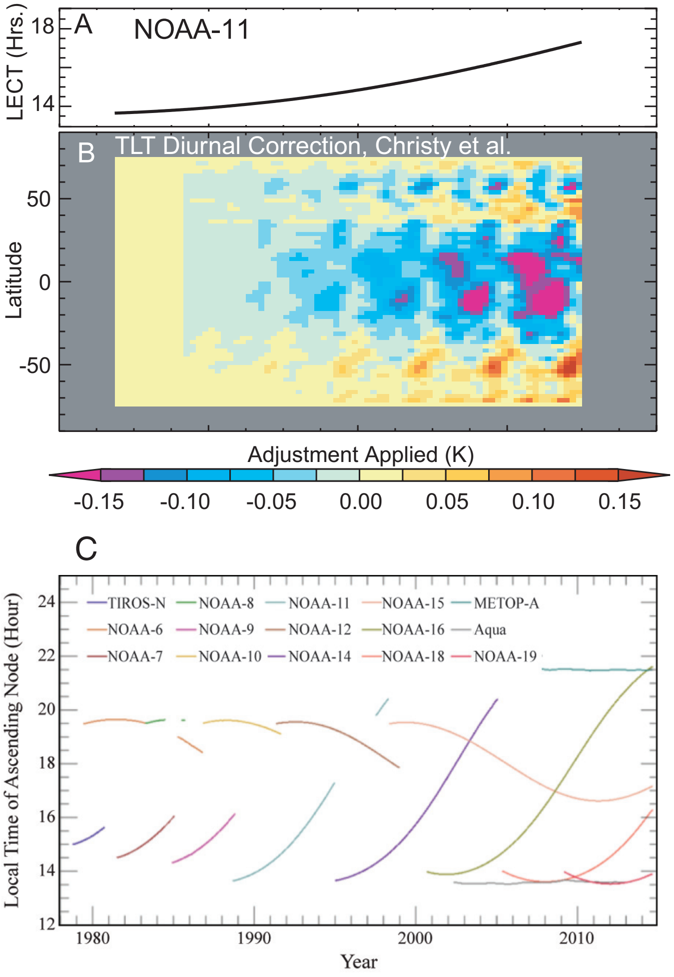

FIGURE 2.4.1 (A) Local equator crossing time for the NOAA-11 satellite plotted as a function of time. (B) Color-coded time-latitude plot of the diurnal corrections applied to lower tropospheric temperature (TLT). (C) Local time of ascending node for the NOAA (National Oceanic and Atmospheric Administration) series of satellites. SOURCE: (A and B) Adapted from C.A. Mears and F.J. Wentz, 2005, The effect of diurnal correction on satellite-derived lower tropospheric temperature, *Science* 309:1548-1551. Reprinted with permission from AAAS. (C) C.A. Mears, M.C. Schabel, and F.J. Wentz, 2003, A reanalysis of the MSU Channel 2 tropospheric temperature record, *Journal of Climate* 16:3650-3664. © American Meteorological Society. Used with permission.

Achieving the required measurement quality in the most cost-effective and risk-free manner may involve changing observation plans over time, especially as new technologies evolve. One such example is the CLARREO mission, whose objectives include serving as an in-orbit calibration reference and thereby greatly reducing space borne instrument calibration drift or shifts in calibration that occur across Type 2 gaps. The quality examples in Chapter 3 and the appendixes provide methods where uneven time and space sampling as well as varying levels of instrument or algorithm uncertainty are utilized in the determination of quality. This flexibility allows for an objective trade space that can accommodate the quality of changing space-borne observations, surface observations, aircraft or suborbital observations, model assimilation such as a weather re-analyses, and any combination of the these data sources. Examples of such analyses can be found for the impact of Type 2 data gaps for TSI (NRC, 2013), as well as for Earth radiation budget measurements (Loeb et al., 2009). Section 3.4.2 includes further discussion of the impact of unplanned gaps on measurement quality.

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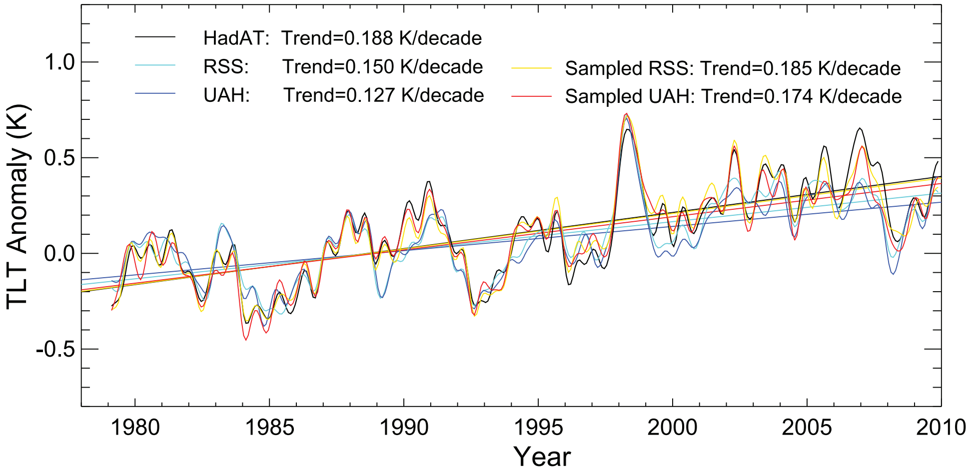

FIGURE 2.4.2 An example of the intercomparison of satellite data from Remote Sensing System, Inc. (RSS; red) and the University of Alabama, Huntsville (UAH; blue); and radiosonde-based data from the Hadley Centre (HadAT; black). For the satellite data, both the true globally averaged time series, and time series found by averaging together only those locations that have radiosonde data are shown. These data have been smoothed to remove variability on time scales shorter than 6 months. SOURCE: C.A. Mears, F.J. Wentz, P. Thorne, and D. Bernie, 2011, Assessing uncertainty in estimates of atmospheric temperature changes from MSU and AMSU using a Monte-Carlo estimation technique, *Journal of Geophysical Research* 116:D08112. Copyright 2011 by the American Geophysical Union.

2.2.4 Data Systems and Delivery for Climate Variables (Algorithms, Reprocessing, and Availability)

The development of climate data records requires the reprocessing[14] of original instrumental raw observations to incorporate gains in knowledge of instrument calibration changes, instrument performance, improved or additional auxiliary data, and new or improved algorithms. For weather applications, the calibration of near real-time satellite measurements and the algorithms that produce geophysical quantities from the measurements, is sufficient for those needs, but must be reevaluated and refined in order to produce climate data records. It is advantageous to retrieve geophysical variables using consistent, state-of-the-art algorithms that evolve as knowledge of relevant processes increases, so that reprocessing of the longer time series is essential to achieve consistent climate data

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[14] For more on reprocessing of climate data records and World Climate Research Programme guidelines for reprocessing, see WCRP (2012).

records. This requires periodic reprocessing of the entire data record using updated corollary data and a single "master" algorithm; it cannot be achieved by the single-pass processing used for operational weather purposes.

Thorough, independent validation of geophysical retrievals often can discern calibration or algorithm errors; conversely, instruments having a consistent calibration and algorithm approach to reprocessing typically provide the continuous data records of the highest quality. For satellite remote sensing observations, the accuracy of long-term, continuous geophysical data products also depends on retrieval algorithms and the effect on these algorithms of changes in instrument characteristics. Achieving continuity in geophysical and climate data products requires use of a consistent, state-of-the-art algorithm for producing the geophysical measurements (Box 2.5). The algorithm

BOX 2.5
Impact of Data Algorithms and Reprocessing on Cloud Optical Properties

Cloud optical thickness and effective radius from MODIS (Moderate-Resolution Imaging Spectroradiometer) have been processed many times to date, each time taking advantage of improved knowledge of instrument radiometric calibration and degradation, and improved knowledge gained from comparisons with ground-based, aircraft, and other space-based assets (e.g., CALIOP [Cloud-Aerosol Lidar with Orthogonal Polarization] on CALIPSO [Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations]). The algorithms used to process these data are continually being improved, and thus reprocessing with state-of-the-art algorithms is essential to establish a high quality long-term data product. Furthermore, the MODIS cloud optical properties algorithm provides pixel-level uncertainty estimates, which are based on errors in the parameters in the processing algorithms, viz., instrument bias and noise, atmospheric correction errors (primarily water vapor), and surface reflectance uncertainty (including ocean reflectance uncertainty due to wind speed). Because of the sensitivity of the measured solar reflectance to these errors, the cloud algorithm estimates will depend on the solar and viewing geometry. Such quantitative error treatment, coupled with state-of-the-art algorithms, requires reprocessing and attention to error sources that is not possible with the one-pass analysis used for timely operational applications.

The National Oceanic and Atmospheric Administration (NOAA) presently operates VIIRS (Visible Infrared Imaging Radiometer Suite), the follow-on to MODIS, in operational weather product processing mode, but has been given only limited funding for VIIRS climate data record processing. The operational weather processing mode does not permit multiple reprocessing and algorithm updates, level-3 gridded and time-averaged global products, or processing time delays to allow updated ancillary information necessary to produce high-quality climate data record. All of these issues must be addressed if the current VIIRS measurements are to be used to continue the MODIS-established climate data records.

Figure 2.5.1 shows ice cloud mean optical thickness for September 2012 derived from three different analyses, one using MODIS observations and two others using VIIRS. The top two panels display results based on nearly identical algorithms applied to two different data sets: MODIS and VIIRS. (The differences are that the MODIS collection 6 cloud product from the Aqua spacecraft uses the MODIS cloud mask and cloud top pressure retrievals while the MODIS-like algorithm applied to the VIIRS data set obtains cloud mask, thermodynamic phase, and cloud top pressure information from a different source due to lack of certain bands being available on VIIRS.)

The bottom two panels display results from two different algorithms applied to the same VIIRS data set. The agreement between the two similar algorithms, but different input files, is quite good, especially in comparison to the operational weather product (bottom panel) where there is an overall negative bias in ice cloud optical thickness due to a different algorithm. This is an example of the need for constant attention to algorithm improvement, periodic reprocessing, and careful error characterization necessary to produce climate-quality Earth science observations. VIIRS is potentially capable of continuing the high-quality Earth science observations begun (in many cases) with MODIS, providing that the algorithms are refined to account for subtle (and sometimes significant) changes in information content of select spectral bands.

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must yield well-characterized products and their uncertainties, and the uncertainty in the measurement must be commensurate with the natural variation in the quantity being measured. The need for reprocessing also requires that the original raw measurement stream from the instrument remain available, and that computing power to fully reprocess the record also be available.

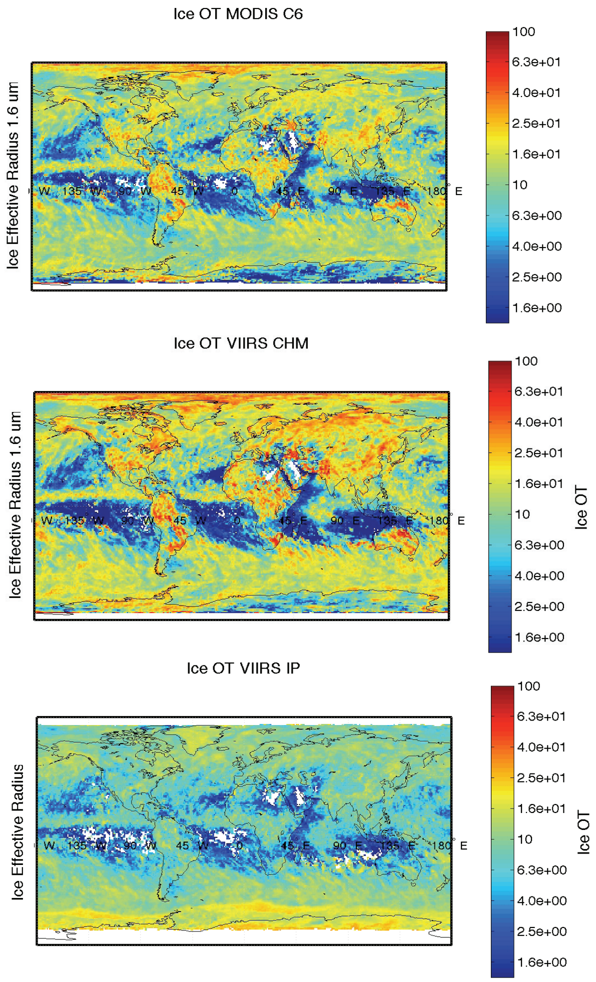

FIGURE 2.5.1 Global September 2012 aggregation of mean ice cloud optical thickness from the Collection 6 MODIS algorithm from Aqua (*top*), MODIS-like algorithm applied to VIIRS (*middle*), and operational weather (IDPS) product derived from VIIRS (*bottom*). NOTE: IDPS, Interface Data Processing Segment; MODIS, Moderate-Resolution Imaging Spectroradiometer; VIIRS, Visible Infrared Imaging Radiometer Suite. SOURCE: S. Platnick, S.A. Ackerman, B.A. Baum, A.K. Heidinger, R.E. Holz, M.D. King, W.P. Menzel, S. Nasiri, E. Weisz, and P. Yang, 2013, *Assessment of IDPS VIIRS Cloud Products and Recommendations for EOS-era Cloud Climate Data Record Continuity*, Report to NASA Headquarters, Washington, D.C.

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3

A Decision Framework for NASA Earth Science Continuity Measurements

3.1 FRAMEWORK FOUNDATION

NASA Earth Science Division (ESD) has established evaluation processes for proposals submitted in response to NASA Research Announcements (NRAs) and Earth Venture Instrument and mission Announcements of Opportunity (AOs). For both NRAs and AOs, the NASA evaluation relies on subjective ratings by experts of a set of evaluation factors. As a complement to the NRA and AO processes, this chapter describes a methodology for quantifying the value of extending the duration of a particular space-borne measurement, a necessary first step in developing a framework for prioritizing among similar competing continuity measurements. The committee's framework, which is proposed for consideration by NASA ESD, uses a simple scoring system to characterize technical and managerial options. Chapter 4 provides examples of applications of the methodology.

Within NASA, choosing among Earth science continuity measurements competing for funding naturally involves weighing risks and benefits under uncertain technical and financial conditions. Development of approaches to rational decision-making under such conditions has a rich history of academic inquiry and provides important insights into the decision process (see Box 3.1). As a first step toward a NASA decision-making framework, the committee focused on methods to evaluate measurement choices. This evaluation step provides the critical foundation for approaches to measurement selection, a second step not covered in this report.

The required elements for a useful decision-making framework are (1) a set of key characteristics suitable for discriminating among measurements; (2) a method for evaluating the measurement characteristics; and (3) a method for rating a measurement based on evaluation of its characteristics (described in Sections 3.2 and 3.3, below). In recognition of the challenges of measurement selection, the committee has sought to avoid being overly prescriptive with inflexible schemes that may also incorrectly weight, or even omit, characteristics. Instead, the committee emphasized defining a framework that is firmly founded on a small, robust set of key characteristics, but retains substantial methodological flexibility with regard to the evaluation of characteristics and rating of measurements.

Framework development follows from the definition of measurement continuity given in Chapter 2. According to that definition, continuity is recognized to exist only when the quality of the measurement is maintained over a required time period and spatial domain. Maintaining quality over an extended period necessarily incurs cost. Accordingly, the *affordability metric* (A) of achieving measurement continuity will clearly be a prime concern in NASA's decision making. Of similar importance, however, is the expected scientific or societal *benefit metric* (B) of the considered measurement. Just as economic cost-benefit analysis attempts to summarize the *value metric* (V)

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BOX 3.1
Decision Theory and the Committee's Framework

In its effort to develop a decision framework for NASA continuity measurements, the committee benefited from the insights of past theoretical inquiry into the decision process and practical application of decision theories to administrative and business decision-making. As articulated in the works of Simon (1977), Brim et al. (1962), and Mintzberg et al. (1976), an organizational decision process can be divided into a set of distinct phases that generally proceed from problem identification, to designing solutions, to evaluating solutions, to choosing between solutions. In the following sections of Chapter 3, the reader will recognize within the committee's recommended framework a first step that is focused on problem identification and subsequent steps that focus on evaluating proposed solutions. The final step of choosing between solutions has been an important focus of classical decision theory (Mintzberg et al., 1976). Proposed criteria for decision making under uncertainty or ignorance[1] fall broadly into high-payoff/high-risk and acceptable-payoff/risk-averse categories. The choice of a particular selection criteria strategy for use with the recommended continuity measurement evaluation approaches is, in the committees' opinion, best left to the NASA decision makers. Accordingly no attempt is made to apply such selection strategies in this report.

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[1] Peterson explains that in decision theory, everyday terms such as *risk*, *ignorance*, and *uncertainty* are used as technical terms with precise meanings. In decisions under risk, the decision maker knows the probability of the possible outcomes, whereas in decisions under ignorance, the probabilities are either unknown or non-existent. Uncertainty is either used as a synonym for ignorance or as a broader term referring to both risk and ignorance (Peterson, 2009, pp. 5-6).

of funding for a particular project or endeavor, a value-centered framework is capable of effectively distinguishing among the relevant Earth measurements, as follows:

$$V = \text{function}\ (B, A)$$

Finding: A value-based approach can enable more objective decisions regarding continuity measurements.

Recommendation: NASA's Earth Science Division should establish a value-based decision approach that includes clear evaluation methods for the recommended framework characteristics and well-defined summary methods leading to a value assessment.

3.1.1 Quantified Earth Science Objectives

A quantitative determination of the value of a measurement can only be accomplished in the context of a quantifiable objective. Accordingly, the starting point for the committee's recommended framework is identification of a relatively small set (i.e., tens) of quantified objectives that are key to addressing the highest-priority, societally relevant scientific goals.

The committee envisions NASA ESD establishing a small set of quantified objectives from the same sources that inform the development of its program plan, notably, the scientific community-consensus priorities expressed in National Research Council (NRC) decadal surveys[1] and guidance from the executive and congressional

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[1] The 2007 Earth science decadal survey (NRC, 2007) highlighted the following emerging regional and global challenges; each of which can be mapped to particular quantified objectives: changing ice sheets and sea level; large-scale and persistent shifts in precipitation and water availability; transcontinental air pollution; shifts in ecosystem structure and function in response to climate change; human health and climate; and extreme events including severe storms, heat waves, earthquakes, and volcanic eruptions.

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branches. Congressionally mandated midterm assessments of the decadal survey afford an additional opportunity for community evaluation of the objectives. Continuity of an established data set will compete with proposed new measurements as well as multi-measurement "intensives," campaigns that may be mounted to, for example, gain a detailed understanding of a particular climate process. The latter proposals should be defined through an objective that could then be evaluated via the committee's proposed framework or whatever similar quantitative, open, and objective evaluation ESD establishes for continuity measurements.

Setting as goals the deeper understanding of the science underlying each of these decadal survey-identified challenges, the committee envisions NASA being able to identify a finite number of quantified objectives for each goal, as well as identifying the highest priority among them. The objectives should provide critical leverage against the identified goals; such objectives will typically focus on challenges with the greatest uncertainty. Objectives may address, for example, causal attribution, process connections among key geophysical variables, or future projections. As implied by its name, it is essential that an objective be framed quantitatively so that the degree of contribution of a single measurement, or set of measurements, can be evaluated for that objective. Representative examples of quantified objectives for likely important global change science goals are given in Box 3.2.

> **Finding: The starting point for a framework that discriminates among competing continuity-relevant measurements is the identification of quantified science objectives.**

> **Recommendation: Proposed space-based continuity measurements should be evaluated in the context of the quantified science objectives that they are addressing.**

As stated in Chapter 1, the committee chose to illustrate the framework with *science* objectives and not *societal-benefit* objectives, primarily because of the perceived difficulty in adequately comparing large numbers of possible applications. However, the recommended continuity framework is, in principle, applicable to cases where the quantified objective in Earth science is replaced by a quantified objective in Earth applications. A methodology for identifying and assessing such objectives would enable the use of the framework for prioritizing measurements with respect to societal-benefit applications.[2]

> **Finding: Quantified objectives in Earth applications can also be a starting point for the recommended framework, if suitably developed.**

> **Recommendation: NASA should initiate studies to identify and assess quantified objectives in Earth applications related to high-priority, societal-benefit areas.**

3.2 FRAMEWORK CHARACTERISTIC: BENEFIT[3]

Through analysis of the continuity examples given in Chapter 2, the committee has identified four key characteristics to define the *benefit metric* (*B*) of a measurement proposed in pursuit of a quantified objective:

1. The scientific importance of achieving an objective (*importance I*),
2. The utility of a geophysical variable record for achieving an objective (*utility U*),
3. The quality of a measurement for providing the desired geophysical variable record (*quality Q*), and
4. The success probability of achieving the measurement and its associated geophysical variable record (*success probability S*).

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[2] For an example of how societal applications might be incorporated into a value framework, see Pellec-Dairon (2012).

[3] In this report, the term "benefit" is used in relationship to a specific measurement, not the scientific goal per se. Accordingly, as stated above, a measurement is seen as having benefit with respect to achieving a particular quantified objective.

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BOX 3.2
Quantified Objectives

The committee's proposed quantitative decision framework is organized around the evaluation of candidate measurements and their contributions to a particular quantified objective(s) in Earth science. A well-formulated quantified objective is

- Directly relevant to achieving an overarching science goal of NASA's Earth Science Division;
- Presented in such a way that the measurements, their characteristics (spatial, temporal resolution) and their calibration (uncertainty and repeatability), and other requirements are traceable to the overarching science goal; and
- Expressed in a way that allows an analytical assessment of the importance of the objective to an Earth science goal and the utility of the targeted geophysical variable(s) for meeting the science objective.

The following are sample quantified objectives for continuity measurements in Earth system science. It is important to recognize that this list is meant for illustration purposes only; it is not a complete list, and the entries are in no particular order.

1. *Narrow the Intergovernmental Panel on Climate Change Fifth Assessment (IPCC AR5) uncertainty in equilibrium climate sensitivity (ECS) (1.5 to 6°C at 90% confidence) by a factor of 2.* ECS is defined as the long-term global temperature change for a radiative forcing equal to a doubling of carbon dioxide (Myhre et al., 2013). Uncertainty in climate sensitivity is one of the major sources of uncertainty in future economic impacts of climate change (Myhre et al., 2013; SCC, 2010) and for a given forcing, most climate change impacts scale with climate sensitivity.

2. *Detect decadal change in the effective climate radiative forcing (ERF) to better than 0.05 W* m^{-2} *(1σ).* To understand the decade-to-decade warming as observed, it is critical to know the ERF for that decade, and particularly how it has changed compared to the previous decade. The recent slowdown in the rate of increase in global mean surface air temperature (see Flato et al., 2013, Box 9.2) has raised questions in the public/policy arena about the scientific understanding of climate change.

3. *Determine the rate of global mean sea level rise to ±1 mm per year per decade(1σ).* Sea level is increasing, rising at an average rate of 2.0 mm per year between 1970 and 2010. The rate estimated for the period of 1993-2010 increased to 3.2 mm per year (Church et al., 2013). From these estimates, the acceleration of sea level rate is about 1 mm per year per decade. We must be able to determine the current acceleration of sea level at this level with high degree of confidence to make timely projections.

4. *Identify the land carbon sink and quantify this globally to ±1.0 Pg C per year aggregating from the 1° × 1° scale.* Currently, the atmospheric O_2/N_2 ratio and the change in atmospheric δ^{13} C indicate a global land carbon sink of 2.9 ±0.8 Pg C per year (1σ) (Ciais et al., 2013; Le Quéré et al., 2014). Because land vegetation removes one quarter of the carbon emitted to the atmosphere, we must be able to determine the locations of and mechanisms for land carbon uptake. This can be achieved by employing satellite data coupled to numerical process models at the 1° × 1° scale over multiple annual cycles.

5. *Determine the change in ocean heat storage within 0.1 W* m^{-2} *per decade (1σ).* Over 90 percent of the recent heat from global warming is stored in the ocean (Rhein et al., 2013). Observation of the ocean heat storage is key to understanding the heat budget of the planet and thus prediction of future climate. The uptake of heat by the ocean is estimated to be 0.5-1 W m^{-2} (Loeb et al, 2012; Trenberth and Fasullo, 2010). Detection of its change by 10-20 percent per decade is essential.

6. *Determine changes in ice sheet mass balance within 15 Gt/yr per decade or 1.5* Gt/yr^2 *(1σ).* Ice sheets are losing mass at an accelerating rate of 300 Gt/yr per decade, or 30 Gt/yr^2. Detecting changes at the 5 percent level is essential for understanding the interactions of ice sheets and climate at the regional level and for improving projections from numerical models.

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The relationship between the framework characteristics and a measurement/quantified objective pair is illustrated in Figure 3.1.[4] This leads to the following general relationship for the benefit of the measurement in terms of its importance, utility, quality, and success probability:

$$B = \text{Function}\ (I, U, Q, S).$$

Additional cross-cutting factors potentially impact both benefit and affordability. Examples include the ability to leverage other measurement opportunities in pursuit of the science objective and the resilience of a geophysical variable record to unexpected degradation (or gaps) in the measurement quality. The definitions of the four characteristics of benefit are given in the following subsections, where the relationships between these characteristics and value are further explored.

3.2.1 Benefit: Importance

The importance of a continuity measurement ultimately relates to the importance that NASA and the scientific community attach to the science goal that the measurement addresses. Within the framework, importance is directly related to the scientific or societal benefit of achieving a quantified objective. The primary method for gauging importance is through science community consensus as expressed in documents such as the decadal survey.

> **Recommendation: NASA, which is anticipated to be a principal sponsor of the next decadal survey in Earth science and applications from space, might task the decadal survey committee with the identification, and possible prioritization, of the quantified Earth science objectives associated with the recommended science goals.**

3.2.2 Benefit: Utility

The utility metric gauges the contribution that an intended geophysical variable record makes to a specified quantified science objective. On one end of the utility spectrum, are cases where only a single geophysical variable is needed to achieve a quantified objective. On the other end of the spectrum are cases where the considered geophysical variable is but one of many needed for addressing an objective. Over this range, the committee ascribes a higher utility rating to geophysical variables that provide essential contributions to objectives and a lower utility rating to geophysical variables that make indirect/minor contributions.[5]

It is important to clearly distinguish between the utility and quality characteristics. Utility represents the value of an optimal or full quality measurement to the objective. Quality is an independent factor that represents how well a proposed measurement meets the uncertainty required for the objective. Another way to state this is that utility is the relevance of a full quality measurement to the objective, while quality is the uncertainty of the measurement relative to the objective requirement.

A number of methods can be used to gauge the utility of a given geophysical variable record (see Chapter 4 for examples). For instance, Observing System Simulation Experiments (OSSE), while not yet sufficiently mature to be used as formal tools for most objectives, can provide important insights on the utility of geophysical variable records.[6] In particular, OSSE analyses performed on the impacts of various geophysical variables for achieving an objective can greatly inform a relative utility rating of the geophysical variables.

Utility can also be gauged by the relative uncertainty of different components of the quantified objective, with a higher utility rating being attached to geophysical variables that address the highest uncertainty objective components. Examples of this approach would include the very different levels of uncertainty for feedback com-

---

[4] Note: The extension of the simple single measurement/quantified objective pair framework depicted in Figure 3.1 to a multitude of benefits is discussed below in Section 3.7. Such an extension is conceptually straightforward, although elucidating all possible objectives of interest may be impossible. This problem can be made tractable if the science community can successfully identify the top tier of objectives.

[5] The proposed framework will give high value to an ancillary measurement(s) required to achieve a quantified objective.

[6] For additional information about OSSEs, see, for example, Masutani et al. (2010).

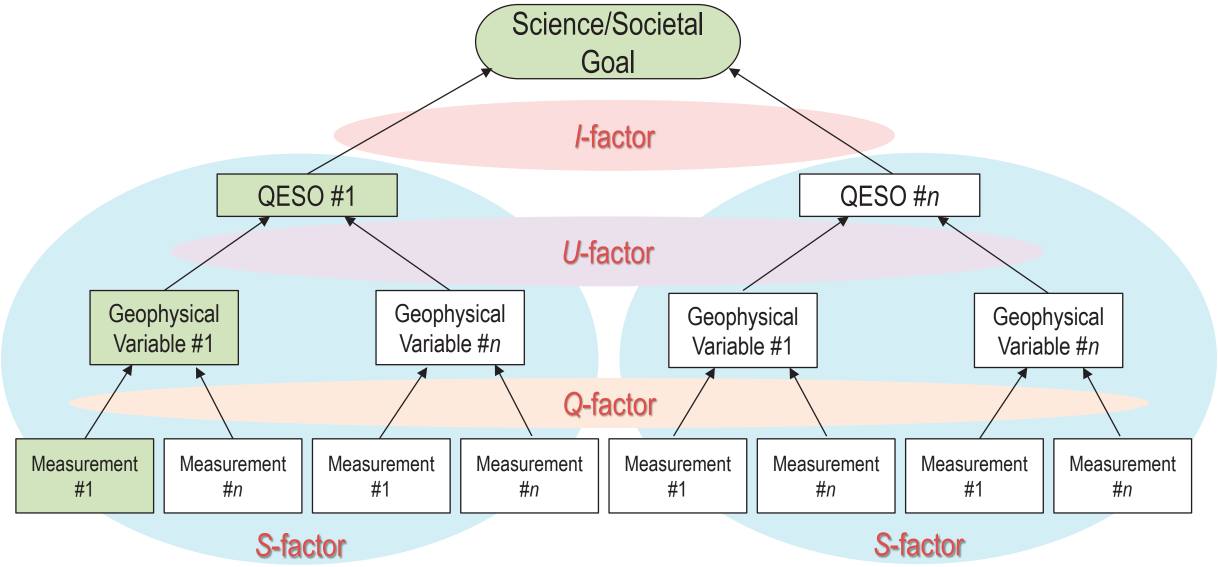

FIGURE 3.1 A schematic representation of the relationship between benefit metric (*B*) factors and key measurement-related terms and characteristics defined in this study—importance (*I*), utility (*U*), quality (*Q*), and success probability (*S*). The shaded areas denote the specific connections between framework factors and the appropriate terms. In particular, the *I*-factor connects an important science/societal goal with one or more quantified Earth science objectives (QESOs). The *U*-factor relates the utility of a particular geophysical variable record to achieving a quantified objective. The *Q*-factor ties together a needed geophysical variable record with the quality of a proposed continuity measurement (and the instrument specific to that measurement). Finally, the *S*-factor broadly connects, through a probability of success analysis, a quantified objective with a geophysical data record and its associated measurements. Evaluation of benefit is accomplished for specific measurement, geophysical variable, objective, and science goal sets (green boxes illustrate an example set for evaluation).

ponents of climate sensitivity or components of anthropogenic radiative forcing (see Section 4.1 and Appendix C for examples).

In the near term, utility may be a more subjective metric given the current limited application of OSSEs for most objectives. In the future, utility metrics can become more quantitative using OSSEs and priorities based on relative uncertainties in addressing the objective. Ultimately, a full Bayesian approach to the quantification of utility is desirable. There is an extensive literature on the use of such approaches for the verification of complex system models such as the climate system (NRC, 2012a). Box 3.3 provides a discussion of the application of a Bayesian approach to the utility and quality characteristics.

> **Finding: The benefit of a measurement is valued by the degree of contribution that the derived geophysical variable record makes to a targeted quantified objective.**
>
> **Recommendation: NASA should foster a consistent methodology to evaluate the utility of geophysical variables for achieving quantified science objectives. Such a methodology could also inform the deliberations of the Earth science and applications from space decadal survey committee.**

3.2.3 Benefit: Quality

The *quality metric* plays a decisive role in determining when a measurement should be collected for durations longer than the typical lifetimes of single satellite missions. This metric derives directly from the measurement characteristics—instrument calibration uncertainty, repeatability, continuity (time and space sampling), and data

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BOX 3.3
Bayesian Methodologies for Evaluation of the Framework Characteristics

The committee recommends a blend of qualitative and quantitative approaches to the key characteristics of *utility* and *quality*. This recommendation is based on current capabilities and understanding as discussed in Chapter 3. Many, if not most, quantified objectives involve the use of measurements to observe the consequences of Earth system processes—to validate the complex physical models of the Earth system used to predict these processes and to determine the uncertainty of the predictions of past, current, and future Earth system behavior.

The National Research Council (NRC) report *Assessing the Reliability of Complex Models: Mathematical and Statistical Foundations for Verification, Validation, and Uncertainty Quantification* (NRC, 2012a; hereafter ARCM), is particularly relevant to the value framework of the current report. ARCM considered a wide range of complex models ranging from aeronautics to combustion to Earth System models. In most cases, the report found that a Bayesian statistical approach can be used to relate the uncertainty in complex models to uncertainty in observations (quality in the current report) and to the relationship between key model parameters and observations (utility in the current report).

As described in ARCM (p. 61), the Bayesian formalism leverages measurements to provide "a set of so-called posterior probability densities of the parameters, describing updated uncertainty in the model parameters." The relationship between a set of measurements and the model parameters can be determined using Observation System Simulation Experiments (e.g., Liu et al., 2014, Feldman et al., 2011). Constructing a posterior probability distribution requires a large set of OSSE (Observing System Simulation Experiment) experiments using a wide range of Earth system models such as the Climate Model Intercomparison Project (CMIP-5) (Taylor et al., 2012) as well as a range of uncertain parameterization values performed in Perturbed Physics Ensembles (Murphy et al., 2004; Stainforth et al., 2005; Smith et al., 2009). A large ensemble of Perturbed Physics OSSEs could, in principle, provide a more quantitative estimate of the utility characteristic consistent with the Bayesian formulation above.

A full Bayesian approach to the value characteristics for continuity in this report would be an ideal long-term quantitative strategy, but practical challenges as discussed in ARCM may limit its full application. These challenges arise due to the large number of parameters and measurements that would be used for many quantified objectives (see examples in the appendixes of this report). Further, Earth system models are expensive to run, while data volumes from hundreds to thousands of full satellite OSSE simulations are at the edge of current computational capabilities. For some objectives, nonlinear changes such as abrupt ocean circulation or ice sheet mass loss as well as very small probability events such as weather extremes would present additional challenges (NRC, 2012a).

Given these difficulties, the current report can only make what is a first step toward a Bayesian statistical evaluation for the framework (primarily for the quantified quality and success probability examples that are in Chapter 3 and the appendixes). As NASA OSSE capability develops in the future, more quantitative utility measures can be added to the framework.

systems and delivery for climate variables (algorithms, reprocessing, and availability)—discussed in the definition of continuity in Chapter 2. The goal or requirement for the quality metric is based on the objectives discussed in Section 3.3.

A number of critical factors define quality. One is the uncertainty and repeatability of the measurement's absolute calibration relative to the quantified science objective requirements. Another factor is the impact of a data gap (see Section 3.4.2, below). For measurements that achieve the quantified objective's uncertainty and/or repeatability requirements, the impact of a data gap must be quantitatively assessed with respect to the lengthening of the time needed to detect a change. The difference in quality of a measurement with, versus without, a gap is determined by the magnitude of the increase in the time needed to detect a change in the presence of a gap. The smaller the increase, the less the impact on the measurement's quality. The difference in quality of the climate

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record with and without continuity of the proposed measurement provides input for continuity decision making: if the difference in the quality metric is small, the continuity observation priority will be low, if the difference is large, the continuity observation priority will be high.

While there are numerous ways to evaluate quality in the context of continuity measurements, a useful metric is expected to vary between continuity required for short-term operational use (weather prediction, agricultural crop monitoring, hazard warnings) versus longer-term science objectives, such as those related to global climate change.[7] Examples for assessing the quality are given in Chapter 4.

Finding: Assessing the quality characteristic of a particular continuity measurement requires knowledge of a measurement's combined standard uncertainty, deriving from the uncertainty of an instrument's calibration uncertainty, repeatability, time and space sampling, and data systems and delivery for climate variables (algorithms, reprocessing, and availability) and the consequences of data gaps on the relevant quantified science objective(s).

Recommendation: The committee recommends that NASA be responsible for refining the assessment approach for the quality characteristic.

3.2.4 Benefit: Success Probability

The success probability metric S is defined as the probability that the measurement being proposed for continuity will successfully meet the goal of extending the specified geophysical record. This metric accounts for such things as the measurement's resilience to gaps (discussed in more detail below) and the possibility of leveraging national and international partners for needed measurements. The success probability metric is also meant to capture—to the extent that they are not covered in the affordability metric—issues that would affect the ability of the proposed measurement to meet the scientific or societal goal. From a decision-theory perspective, S can be seen to address uncertainty in the decision-process by "derating" the maximum potential benefit for known risks to measurement quality. Factors that should be included in deriving S include the risks of the instrument development itself, as well as risks of the associated algorithms needed to achieve the predicted accuracy; an example derivation is given in Chapter 4.

The quality characteristic, through the definition of the calibration uncertainty, and the success probability characteristic are both affected by the impact of gaps and their probability of occurrence. For observations where overlap is critical to maintain higher quality, gaps will affect the quality rating with and without continuity, as well as the success probability, through the risk of a gap occurring. Those measurements whose calibration is sufficiently certain to meet global change requirements will have high quality rating, and their success probability rating will also be high due to smaller impacts of data gaps.[8] *As a result, gap impact on quality, gap risk of occurrence, and gap effects on observing system costs can all be accounted for in the current framework.*

Finding: Success probability is assessed by evaluating the maturity of the measurement instrumentation and algorithms, the risk-posture of the mission implementation approach, the resilience of the geophysical variable record to measurement gaps, and the degree to which alternate approaches, including those from national and international partners, can provide acceptable bridging measurements.

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[7] The committee notes that the quality requirements for measurements related to climate change quantified objectives will tend to be most stringent at global scale, and less stringent at zonal or regional scale. Instrument accuracy and repeatability will therefore be driven by global average analysis as in the examples in this report. However, the committee's analysis framework can be used at any spatial scale required by the objective. In general, anthropogenic climate change signals appear first in global averages since natural variability typically decreases with increasing spatial averaging. Natural variability at zonal and regional scales can be factors of 3 (zonal) or 10 (regional) larger than global averages (e.g. Wielicki et al., 2013).

[8] Note that those instruments which make accurate measurements (i.e., with calibration uncertainty sufficient to meet the quantified objective) could be launched less often since gaps for short time periods are unlikely to degrade the fidelity of the long-term record: this could translate to significant cost savings in the affordability metric.

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3.3 FRAMEWORK CHARACTERISTIC: AFFORDABILITY

Affordability is the cost per year of continuing the prescribed measurement for a specified time period with the required quality, relative to the total budget that NASA has allocated for all satellite measurements.

To achieve the required quality, the measurement must have the uncertainty, repeatability, time and space coverage, and reduction algorithms to meet the scientific requirements. The cost is the full funding needed to make the observations and produce the measurement for a finite length of time: it includes instrument development; space platform accommodation; launch; on-orbit collection; validation; algorithm implementation; science team contributions; and data algorithm (re)processing and testing facilities, archiving, and distribution. Should multiple overlapping measurements be prescribed to preclude gaps to achieve the needed repeatability of the measurement over the specified time, they are also part of the cost.[9] Included as well are additional factors that reduce risk, such as advancing the instrument TRL and auxiliary observations, should they be needed, to implement the algorithms that produce the measurements. To the extent that factors such as TRL, gap mitigation, validation, and algorithm maturity development are included in the measurement cost, they may enhance the reliability of the associated success probability estimate of the measurement. Thus, cost shares a number of cross-cutting characteristics with utility, quality, and success probability that must be quantified and implemented in the value metric.

Finding: Assessing affordability requires comprehensive cost analysis from measurement to geophysical variable record and includes risk mitigation.

Recommendation: NASA should extend their current mission cost tools to address continuity measurement-related costs needed for the decision framework.

3.4 CROSS-CUTTING ISSUES

The committee identified the following cross-cutting issues that do not easily group into any one of the aforementioned framework criteria—measurement calibration uncertainty, repeatability, time and space sampling, and data systems and delivery for climate variables (algorithms, reprocessing, and availability), but instead apply to multiple criteria.

3.4.1 Leveraged Measurements

Leveraging is a factor that the framework takes into account via the success probability and affordability of a proposed measurement. It can be an important consideration for many proposed measurements; for example, collaboration with international partners can serve as a demonstration of a broad acceptance in the global community of the importance of a measurement, and has the potential to reduce the required contribution of individual partners. In a 1998 NRC report, a joint committee of the Space Studies Board and the European Space Science Committee identified the following as elements essential to successful international cooperation in space research missions (NRC, 1998, p. 3):

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[9] The impact of interagency and international collaboration on cost can be accounted for in the committee's proposed decision framework. Consider the following three cases: (1) NASA and Sponsor A are flying similar instruments and coordinate their launches to provide an extended data record; (2) Sponsor A is operating instrument A to measure variable A, and NASA launches instrument B into a similar orbit to measure variable B, which can be combined with variable A to produce variable C; and (3) Sponsor A is developing an instrument with various channels or frequencies to measure variable A, and NASA offers to provide some funds for additional channels/frequencies to measure variable B. Especially for a foreign partner, Case 3 would appear to be unlikely because of risk and the restrictions imposed by International Traffic in Arms Regulations, although there have been notable exceptions (e.g., Jason and GRACE). For Case 2, the collaboration between Sponsor A and NASA will be reflected in changes in the scoring of the quality metric (versus adjustments in affordability). Finally, the framework's treatment of Case 1 is the same for gaps in the data record. As noted above, should multiple overlapping measurements be prescribed to preclude gaps to achieve the needed repeatability of the measurement over the specified time, they are also part of the cost. In Case 1, Sponsor A's launch of a similar instrument (at no cost to NASA) will be reflected in the framework by the assignment of a higher affordability rating for the NASA effort.

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1. *Scientific support*—compelling scientific justification of a mission and strong support from the scientific community. All partners need to recognize that international cooperative efforts should not be entered into solely because they are international in scope.
2. *Historical foundation*—partners have a common scientific heritage that provides a basis of cooperation and a context within which a mission fits.
3. *Shared goals and objectives for international cooperation* that go beyond the objectives of scientists to include those of the engineers and others involved in a joint mission.
4. *Clearly defined responsibilities* and a clear understanding of how they are to be shared among the partners, a clear management scheme with a well-defined interface between the parties, and efficient communication.
5. *Sound plan for data access and distribution*—a well-organized and agreed-upon process for data calibration, validation, access, and distribution.
6. *Sense of partnership* that nurtures mutual respect and confidence among participants.
7. *Beneficial characteristics*—successful missions have had at least one (but usually more) of the following characteristics:
   a. Unique and complementary capabilities offered by each international partner;
   b. Contributions made by each partner that are considered vital for the mission;
   c. Significant net cost reductions for each partner, which can be documented rigorously, leading to favorable cost-benefit ratios;
   d. International scientific and political context and impetus; and
   e. Synergistic effects and cross-fertilization or benefit.
8. *Recognition of importance of reviews*—periodic monitoring of mission goals and execution to ensure that missions are timely, efficient, and prepared to respond to unforeseen problems.

Leveraging can also occur in collaborations among U.S. federal agencies and in joint programs such as the U.S. Geological Survey-NASA partnership for Landsat.[10] Finally, it is important to consider not only leverage opportunities for space-based missions, but also interagency or international collaborations involving space- and in situ-based instruments.

3.4.2 Gap Risk Evaluation

Early in its discussions, the committee included "gap risk" as an independent characteristic in the value framework. It rapidly became clear, however, that gap risk affects many of the other characteristics in the value framework and, therefore, should be addressed as part of those factors.

First, the occurrence of a gap can increase the uncertainty and decrease the repeatability of a geophysical variable record (Loeb et al., 2009; NRC, 2013) and, therefore, affect the quality characteristic for that record. The primary effect on quality arises from discontinuities between successive measurements in a long-term geophysical variable record without sufficient absolute calibration uncertainty of the measurement. Another quality impact can occur if there are time-space gaps in a perfectly calibrated satellite measurement record (usually over several years) that miss the key variability needed to define a geophysical variable record (e.g., volcanic eruptions or the ability to average over internal natural variability such as the El Niño southern oscillation).

Second, the statistical likelihood of a data gap depends on instrument and spacecraft reliability design, launch schedules, as well as existing instruments and their age in orbit. All of these factors in the observing system design will affect the success probability of achieving a geophysical variable record of desired quality (Loeb et al., 2009).

Third, the strategy to avoid gaps will involve instrument and spacecraft reliability and launch schedules. These factors will then drive cost and the associated affordability factor. *For these reasons, a careful gap risk analysis is required as part of the value analysis, but gap risk must be considered in three of the characteristics (quality, success, and affordability) and cannot be treated as a single factor*.

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[10] Factors influencing the success of these collaborations are reviewed in detail in (NRC, 2011).

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3.5 FRAMEWORK INPUT

The key framework characteristics are defined in the preceding sections. In the following chapters, the committee discusses possible approaches for quantitatively evaluating framework characteristics and for calculating value based on functional relationships between the characteristics. Regardless of the approach taken for judging the value of a continuity measurement, a uniform set of information is required for the recommended framework to be successfully applied. The committee envisions that future NASA discussions of proposed continuity measurements will use—in analogy with current ROSES (Research Opportunities in Space and Earth Sciences) and AO solicitations—well-established guidelines for submitting advocacy information. An example of such a guideline for continuity measurements is shown in Box 3.4.

3.6 DETERMINING CONTINUITY MEASUREMENT VALUE

Having identified the key value characteristics in the previous sections, the committee sought a robust approach for rating the value of a continuity measurement based on evaluations of its key characteristics. To be useful, the framework must successfully differentiate among the hundred or more climate-related geophysical variables of interest (e.g., there are approximately 50 Global Climate Observing System (GCOS)-established essential climate variables[11]), and also among the larger number of instrument data records that potentially can be used to provide measurements of sought after geophysical variables. Ideally, the chosen approach would involve rigorous analytical evaluation methods that can yield precise quantitative ratings.

Among the many rating approaches considered, two were identified by the committee as having particular merit. The first approach, similar to that used by NASA for evaluating proposals submitted in response to NRAs or Earth Venture AOs, relies on subjective ratings by experts of a set of evaluation factors (see Box 3.5). Whereas NRA evaluations are focused on programmatic relevance, intrinsic merit, and cost realism, and AO evaluations are focused on scientific merit, scientific implementation merit and feasibility, and technical, management, and cost feasibility (including cost risk) of the mission implementation, a continuity measurement would be evaluated using questions related to key value characteristics, namely

- Does it address an important scientific objective requiring continuity? (Importance)
- Will it contribute substantially to the objective? (Utility)
- Does it have sufficient quality to contribute to the objective? (Quality)
- Can the quality be readily obtained and maintained? (Success Probability)
- Is it affordable within the available NASA budget? (Affordability)

Similar to the NRA and AO cases, the committee envisions an overall continuity measurement value rating being derived from summary analysis of the individual evaluations. The use of a five-level summary rating system (see Table 3.1) should provide sufficient discrimination for NASA to divide proposals between “selectable” and “not selectable” and identify the fraction of proposals to fund (Table 3.2). For continuity measurements, where there is a substantially larger cost commitment and, hence, smaller fractions of supportable proposals, the need to increase proposal discrimination is apparent. Several approaches can be used to create higher discrimination, including increasing the number of rating levels for evaluation criteria, creating a higher threshold definition for the top rating category, giving higher weights to more readily quantifiable evaluation criteria (e.g., cost), or sequencing the criteria evaluations in ways that progressively distill the measurement candidates (e.g., a series of elimination gates).

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[11] The goal of the Global Climate Observing System (GCOS) is to provide comprehensive information on the total climate system, involving a multidisciplinary range of physical, chemical, and biological properties and atmospheric, oceanic, hydrological, cryospheric, and terrestrial processes (GCOS, “About GCOS,” https://www.wmo.int/pages/prog/gcos/index.php?name=AboutGCOS, accessed April 6, 2015). GCOS identifies essential climate variables (ECVs) that are both currently feasible for global implementation and are required to support the work of the Intergovernmental Panel on Climate Change and the UN Framework Convention on Climate Change. See GCOS (2010). The 50 GCOS ECVs are listed at GCOS, “GCOS Essential Climate Variables,” http://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables, accessed April 6, 2015.

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BOX 3.4
Guidelines for Continuity Measurement Framework Input

1. **Identify the quantified objective(s) the proposed measurement under construction addresses (see Box 3.2).**

2. **Describe the *importance* of the quantified objective to a high-priority, societally relevant science goal.**
   a. Description should be short, referenced, but understandable to a broader audience.
   b. Provide a perspective on how the objective fits within the broader scientific issues of understanding global change.
   c. Provide a perspective on how the objective benefits society, beyond the science.

3. **Explain the *utility* of the measured geophysical variable(s) to achieving the quantified objective.**
   a. Explanation of the geophysical variables to be provided by the mission / measurement(s).
   b. Description of the utility of these variables in terms of the *relative fraction*[1] they contribute to answering the objective.
   c. A list of auxiliary data required to deliver the proposed measurement(s), but not part of the proposed mission, delineated by program and instrument.

4. **Detail the *quality* of the measurement relative to that needed for the quantified objective.**
   a. Assess the quality of the proposed measurement against the requirements of the objective.
   b. Includes, inter alia, instrument calibration uncertainty, repeatability, time and space sampling, and data systems and delivery for climate variables (algorithms, reprocessing, and availability) of all data products.
   c. Assess the ability to satisfy the objective both with and without proposed observation(s).

5. **Discuss the *success probability* of achieving the measurement.**
   a. Provide an assessment of the heritage and maturity of proposed instruments and data algorithms.
   b. Assess the likelihood of leveraging similar or complementary non-NASA measurements.
   c. Provide a quantitative analysis of the risk of a gap in the measurement and the effect of that gap on the quality of the long-term record and its ability to remain useful in meeting the objective.

6. **Provide an estimate of the *affordability* of the measurement.**
   a. Estimate the total cost of the proposed observation(s).
   b. Include the expected years of record on orbit at reasonable levels (e.g., 85%) of reliability.
   c. Include additional costs to mitigate unacceptable risks of measurement gaps.

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[1] Regarding 3b and "relative fraction": In this report, the committee notes that its evaluation methods for the importance and utility characteristics are subjective; however, it recommends (in Chapter 3) that the sum of the utility ratings of all observations needed by the quantified objective be equal to 1.0. This allows the framework to account for some observations being more important than others, while avoiding a "check the box" process that just counts the number of observation sources without consideration of relative importance. It also normalizes the utility rating of all objectives to the same numerical scale, thereby allowing an "apples-to-apples" comparison. The report also shows a path toward future more rigorous and objective analysis of utility using the Bayesian framework discussed in Box 3.3.

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BOX 3.5
Suggested Evaluation Factors for Continuity Measurement Proposals

Unless otherwise specified by NASA, the principal elements (of approximately equal weight) considered in evaluating a continuity measurement are the importance of the scientific objective being addressed (importance), the contribution of the measurement to the science objective (utility), the quality of the measurement for addressing the objective (quality), the likelihood that the measurement can be developed and maintained (success probability), and the affordability of the continued measurement within the NASA budget (affordability).

- Evaluation of a measurement's importance considers documented community priorities for science goals and quantified science objectives.
- Evaluation of a measurement's utility includes consideration of all of the key geophysical variables, and their relative contributions, for addressing a quantified objective.
- Evaluation of a measurement's quality includes consideration of its uncertainty, repeatability, time and space sampling, and data algorithm characteristics relative to that required for achieving a targeted scientific objective.
- Evaluation of the measurement's success probability includes consideration of the heritage and maturity of the proposed instrument and its associated data algorithms, the likelihood of leveraging similar or complementary measurements, and the likelihood of data gaps that would adversely affect the quality of the measurement.
- Evaluation of the affordability of a proposed continuity measurement includes consideration of the total cost of developing, producing, and maintaining the sought-after data record. The impacts of gap mitigation on cost are included in this consideration.

TABLE 3.1 Adjectival "Value" Scale for Proposed Continuity Measurements Versus Framework Rating

Analytical Method Score (from Chapter 3)	Description	Rating $I \times U \times Q \times S$
Poor	A continuity measurement of low value that provides little benefit regardless of affordability.	0 - 5
Fair	A continuity measurement that provides value but with neither of the benefit and affordability characteristics being above average.	6 - 10
Good	A continuity measurement of moderate value with only one of the benefit and affordability characteristics being above average	11 - 15
Very Good	A continuity measurement of high value with above average benefit and affordability characteristics.	16 - 20
Excellent	A continuity measurement of exceptional value that provides maximum benefit and is highly affordable.	21 - 25

TABLE 3.2 Comparison of Summary Evaluation Methods

Evaluation Metric	Subjective Method Ratings	Analytical Method Scores (from Chapter 3)
Importance (*I*)	Low, Moderate, High, Very High, Highest	1 - 5
Utility (*U*)	Low, Moderate, High, Very High, Highest	0 - 1
Quality (*Q*)	Low, Moderate, High, Very High, Highest	0 - 1
Success probability (*S*)	Low, Moderate, High, Very High, Highest	0 - 1
Affordability (*A*)	Low, Moderate, High, Very High, Highest	1 - 5
Overall value (*V*)	**Poor, Fair, Good, Very Good, Excellent**	**0 - 25**

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A second ratings approach considered by the committee adheres more strongly to a typical "cost-benefit" analysis. The potential advantage of this approach is more reliance on well-prescribed quantitative analysis and less on subjective evaluation. A simple manifestation of this approach is[12]

$$V = B \times A = (I \times U \times Q \times S) \times A$$

Successful implementation of this approach requires determining the relative weights of the benefit and affordability terms and defining the ratings scales of the individual benefit terms in a way that maintains the relative B and A weights. A self-consistent method would be to (1) assign ratings scales (e.g., 1 to 5) to the importance and affordability[13]—terms that reflect the desired relative weights for B and A, and (2) define the utility, quality, and success probability rating scales in terms of percentages. In this formulation, the rating of B can be understood as follows:

$B = I$ (maximum potential benefit) $\times$ $U \times Q \times S$ (percentage of maximum benefit realized),

where

I = importance of the quantified objective = maximum potential benefit,
U = percentage of the quantified objective achieved by obtaining targeted geophysical variable record,
Q = percentage of required geophysical variable record obtained by proposed measurement, and
S = probability that proposed measurement will be successfully achieved.

In Chapter 4, the committee describes its examination of various methods for defining and quantifying characteristic ratings and for calculating the cost-benefit value. Not surprisingly, the committee's examination revealed the inherent challenges in moving from subjective to analytical evaluations. *As a result, the committee explored a hybrid approach that combines subjective ratings for I, semi-analytical ratings for U and S, and analytical ratings for Q and A.*

Finding: A number of potentially useful methods exist for prioritizing among continuity measurements.

Recommendation: NASA should establish a value-based decision approach that includes clear evaluation methods for the recommended framework characteristics and well-defined summary methods leading to value assessment.

3.7 EXTENDING THE FRAMEWORK BEYOND SINGLE CONTINUITY MEASUREMENT/QUANTIFIED OBJECTIVE PAIRS

As described above, the decision framework is designed to assess a single continuity measurement for a single quantified objective. As such, it illustrates a general approach to comparing different objective/continuity measurement pairs. In deciding whether to pursue a particular continuity measurement, NASA managers may seek answers to some additional questions, such as the following:

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[12] The committee debated at length regarding the choice of framework characteristics; the object was to derive a minimal set of largely independent characteristics that would provide meaningful evaluations of proposed continuity measurements. That the factors are not completely independent in a statistical sense is recognized. For example, success probability and affordability are not completely independent; however, the relationship between them is sufficiently complex that it was necessary to retain both in the framework. As an example: NASA's ability to "buy down" risk (i.e., increase S by decreasing A) is not easily quantified for complex technologies; similarly, accounting for the strategic plans of other national and international partners—a difficult problem—is easier to handle in a framework with separate success and affordability factors. Accordingly, the committee elected to retain both the success probability and affordability characteristics. By retaining success probability, the treatment of uncertainty in the decision process is more readily achieved.

[13] The committee does not assign a zero value to I or A because no measurement would be under consideration if it has no importance, and A would only be zero in the case of infinite cost.

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1. How does the value of a continuity measurement compare to that of a new measurement?
2. For any single objective, which measurement (or set) provides the most value?
3. What is the total value of a single measurement relative to all objectives of interest?

All three questions are relevant when considering how best to address the highest-level objectives identified by the science community (i.e., decadal survey recommendations). Addressing question 1 requires that objectives be defined at a relatively high level of scientific inquiry so as to accommodate considerations of new measurements. In particular, a new measurement is justified by either a new objective that is not amenable to the existing observing systems, or by some significant weakness apparent in the current system that addresses an established objective. In the context of an established objective, need for new measurements may arise from improvement in utility, quality, or cost in meeting the objective. Given an appropriate objective, a new measurement would be handled within the decision framework in a manner identical to that of an existing measurement.

Addressing questions 2 and 3 can be readily accomplished within the recommended framework by repetitive application of the methodology to each of the measurements contributing to a single objective or to each of the objectives pertaining to a single measurement, respectively. For question 3, an evaluation of the total value of a measurement requires the development of an appropriate summary methodology.

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4

Applying the Framework to Continuity Measurements

4.1 INTRODUCTION

Implementing the decision framework described in Chapter 3 requires methods to evaluate the affordability and each of the key benefit characteristics. These evaluations are then used to derive an overall value rating. The goal of this chapter is to identify analytic evaluation approaches that are enabled by a quantified objective-driven framework.

4.2 EVALUATING IMPORTANCE AND UTILITY

Among the five value characteristics, importance and utility most reflect value judgments of the broader science community. As mentioned in Section 3.2.2, observational simulation tools are, increasingly, used to inform subjective evaluations of the utility characteristic. Other sources of information include the Earth science and applications from space decadal survey and, possibly, other appropriate community forums, which could assist in the identification of the quantified objectives of highest importance along with corresponding lists of high utility measurements.

For a numerical cost-benefit approach, and by analogy with the NASA Research Announcement (NRA) scheme shown in Table 3.1, the evaluation of the importance factor would correspond with the top levels[1] (e.g., 4 and 5) of a 1 to 5 rating system (Table 4.1). For the evaluation of the utility of a particular geophysical variable, the numerical rating is desired in percentage terms relative to achieving maximum benefit (Table 4.2). A simple approach would be to assign ratings between 0.8 and 1 (complete benefit) for the highest utility measurements. One caveat is that pursuit of some quantified objectives may depend, nearly equally, on many geophysical variable records. For those cases, the ratings will be uniformly low across the important variables. For such cases, it might be more appropriate to consider the set of measurements as an integrated observing system and assess value as discussed in Section 3.7 (Utility Example 2).

As an example scenario, the decadal survey might identify and evaluate the six quantified objectives given in Box 3.2 and the associated geophysical variables given in Table 4.3. Under that scenario, some or all of the

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[1] Here it is assumed that in practice only quantified Earth science objectives with importance rankings of very high or better will be considered for framework analysis.

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TABLE 4.1 Subjective Method Ratings for Importance (*I*)

Rating for *I*	Analytical Method Score (from Chapter 3)
1	Low
2	Moderate
3	High
4	Very high
5	Highest

TABLE 4.2 Subjective Method Ratings for Utility (*U*)

Rating for *U*	Analytical Method Score (from Chapter 3)
0.2	Low
0.4	Moderate
0.6	High
0.8	Very high
1.0	Highest

objectives might emerge as most important (rating = 5) with a small number of the relevant geophysical variables achieving a similarly high utility rating (e.g., 1).

In the examples below, it is important to keep in mind the clear distinction between the utility and quality characteristics. Utility is the relevance of an optimal measurement to the objective, while quality is the uncertainty of the measurement relative to the objective requirement.

4.2.1 Utility Example 1: Earth Radiative Forcing Change

The recent slowdown in the rate of increase in global mean surface air temperature has raised questions in the public/policy arena about the scientific understanding of climate change, with renewed focus on elements of climate forcing over the 1998-2012 period.[2] The effective radiative forcing (ERF) from the well mixed greenhouse gases has increased at a rate of about 0.3 W m^{-2} per decade over the past 3 decades, while all other forcings (except for stratospheric volcanic aerosols) are estimated to have changed by less than 0.05 W m^{-2} (Myhre, 2013, Appendix II). While the slowdown was relatively large (about 0.04 °C $decade^{-1}$ vs. 0.11 °C $decade^{-1}$ for the previous several decades), it might readily fall within climate variability if the ERF were only 0.2 W m^{-2}, and recent work has suggested small corrections to the ERF over the period of as little as 0.05 W m^{-2} might explain or contribute to the slowdown (Huber and Knutti, 2014).

These considerations lead us to pose the detection of a change in climate forcing (i.e., ERF) to better than 0.05 W m^{-2} as a quantified objective (see Box 3.2). While radiative forcing observations are critical to understanding decadal change such as the slowdown in global warming, they are not the only information required. Other data, involving other objectives are required for a full understanding of cause and effect in the climate system, including the role of internal natural variability of the coupled ocean/atmosphere system.

To evaluate the utility of geophysical variables in constraining ERF to levels of 0.05 W m^{-2}, the variables are divided into four levels based on their uncertainty over a decade, namely, <0.003 W m^{-2}; 0.003 to 0.01 W m^{-2}; 0.01 to 0.05 W m^{-2}; >0.05 W m^{-2}. Numbers for this analysis have been taken from the 2013 IPCC Working Group I data tables (IPCC, 2013) and the NOAA TSI workshop report (NOAA, 2013). Note that a number of key indirect effects that might change the CO_2 or CH_4 abundance are not considered here since changes in the well mixed greenhouse gas abundances are being measured from ground-based networks at the necessary level.

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[2] See Box 9.2 in Flato et al. (2013). More recently, Trenberth (2014) have published papers that explain the slowdown in surface warming in terms of disposition of energy within the ocean and climate system. See Trenberth (2014). Also see, Meehl (2014).

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TABLE 4.3 Key Geophysical Variables and Instrument Data Types Associated with the Measurements Needed to Address the Example Quantified Objectives

Quantified Objective	Relevant Geophysical Variables	Example Instrument Data Types
Equilibrium Climate Sensitivity	• TOA broadband solar reflected flux • TOA broadband thermal infrared-emitted flux • Ocean heat content change and distribution • Cloud fraction • Cloud optical depth • Cloud particle phase • Cloud particle size • Surface air temperature • Air temperature profile • Air water vapor profile • Surface albedo snow and ice • Surface cover snow and ice	• Upwelling Earth radiation • Passive VIS/IR and microwave radiances • Broadband longwave radiances • Spectrally resolved solar irradiances • GNSS (Global Navigation Satellite System) radio occultation bending angles • In-situ ocean heat content profiles from the Argo network • Bulk temperature from altimeter and GRACE measurement differences
Earth Radiative Forcing Change	• Total and spectral solar-irradiance • Surface albedo • Aerosol optical depth (including stratospheric) • Aerosol vertical distribution • Aerosol particle size • Aerosol type • Aerosol single scatter albedo • Cloud properties (shown above; for aerosol indirect effects) • Trace-gases (CO_2, CH_4, N_2O, CO, NO_x, Halocarbons, tropospheric and stratospheric O_3) • Stratospheric H_2O	• Solar occultation spectrometry • Passive VIS/IR and microwave radiances • Broadband longwave radiances • Spectrally resolved solar irradiances, UV/VIS/IR limb sounding (scatter, emission, occultation)
Sea Level Rise Acceleration	• Sea level • Glacier mass • Ice sheet mass • Ocean temperature profile • Land water storage mass	• Altimetry—active microwave (From exact repeat orbit.) • Interferometry SAR • Terrestrial Reference Frame and associated surface-based tracking stations • Gravity change measurements • In-situ ocean heat content profiles from the Argo network
Land Carbon Sink	• Atmospheric CO_2 concentrations • Land photosynthesis • Land vegetation biomass disturbance and biomass burning • Respiration/decomposition	• Reflected solar spectrometry • Moderate-resolution multispectral VIS/NIR • Imager radiances • High-resolution multispectral VIS/NIR, TIR, lidar, and long-wavelength radar • MODIS/VIIRS and SMAP
Ocean Heat Storage Change	• Ocean temperature profile • Sea level • Mass component of sea level (glaciers, ice sheets, river runoff)	• Gravity • Radar altimetry
Ice Sheet Mass Balance Change	• Ice sheet mass • Ice sheet elevation • Ice sheet velocity • Ice sheet base topography • Ocean temperature profile near ice sheet edge	• Surface interferometry • Radar and laser altimetry, supplemented by SAR • Broadband radiances • Gravity change measurements • Spectrally resolved solar irradiances VIS/IR radiances, VIS/IR imager radiances

NOTE: GNSS, Global Navigation Satellite System; GRACE, Gravity Recovery and Climate Experiment; IR, infrared; MODIS, Moderate-Resolution Imaging Spectroradiometer; SAR, synthetic aperture radar; SMAP, Soil Moisture Active-Passive; TIR, thermal infrared; TOA, top of the atmosphere; UV, ultraviolet; VIIRS, Visible Infrared Imaging Radiometer Suite; VIS, visible.

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The geophysical variables that need to be evaluated from space for this objective include: total and spectral solar irradiance, surface and cloud properties and albedo, tropospheric and stratospheric volcanic emissions, tropospheric aerosols, cloud properties (including aerosol indirect effects), and trace gases, including tropospheric and stratospheric O_3, and stratospheric H_2O. Other aspects of overall radiative forcing can be evaluated using ground based measurements. Ancillary measurements include the radiation budget for a constraint on the total forcing.

From among these variables, those having the highest utility rating are cloud-properties/albedo, stratospheric/volcanic aerosols, tropospheric aerosols, and tropospheric ozone. For clouds, a 1 percent change in cloud albedo corresponds to about 0.8 W m^{-2}, and hence a shift in cloudiness (~1%) that occurs during a decade but is not documented represents a major gap in closing the ERF trends. For volcanic stratospheric aerosols, the change in ERF from the 1990s decade (–0.7 W m^{-2}) to the 2000s decade (–0.1 W m^{-2}) is huge (Boucher et al., 2013). Without satellite observations, the ERF from a Pinatubo-like eruption would not have been well measured, and, thus, the gap error might be a substantial fraction of the change in the volcanic ERF in the 1990s, –0.7 W m^{-2}.

For tropospheric O_3, changes are space-time variable like aerosols and clouds and cannot be determined from ground-based observations alone; satellites have the potential capability to detect trends in the quantities that determine ERF. The emissions that create tropospheric O_3 are shifting dramatically over the decade (but not year by year) as new areas of industry and pollution arise and as old regions (United States and the European Union) dramatically reduce pollution. Thus, tropospheric O_3 ERF appears to be changing very slowly recently; but independent, geographical shifts forced by emissions are driving change. The committee estimates the uncertainty over a decade due to current shifts in emission regions to be at least 20 percent of the total, or 0.08 W m^{-2} $decade^{-1}$. For tropospheric aerosols, the ERF from anthropogenic sources is estimated to be –0.9 W m^{-2}. Given the decadal shifts in regional emissions, this has similar uncertainty in the case of satellite gaps as tropospheric O_3, ~20 percent per decade or ~0.18 W m^{-2}. Uncertainties in other geophysical variables such as total solar irradiance, surface properties/albedo and stratospheric O_3 are seen to be changing more slowly and with less uncertainty.

The above analysis suggests that sustained, multidecadal spaceborne measurements of tropospheric O_3, stratospheric aerosols, tropospheric aerosols, and cloud properties are of highest utility for addressing the quantified objective for ERF.

4.2.2 Utility Example 2: Land Carbon Sink

Since 1960, the atmospheric CO_2 concentration has risen from 315 ppm to 400 ppm and is growing at the rate of 2 ppm/year (Dlugokencky and Tans, 2015). Atmospheric CO_2 concentrations would be even higher if it were not for large carbon uptakes or sinks by both terrestrial vegetation and the oceans, which remove about half of CO_2 emissions (Figure 4.1). While the carbon cycle is known globally, regional knowledge is lacking. This is especially true for the land carbon sink that not only has high inter-annual variations, but has a large quantity of stored carbon in plants and soils. Whether land vegetation will continue to absorb half of future CO_2 emissions is unknown. Improvements in understanding of the land carbon sink are needed to predict future trajectories of atmospheric carbon: data from satellite observations coupled with numerical process models are critical in this effort and the only way this can be achieved.

The challenge in addressing a quantified objective focused on understanding of the land carbon sink is that all of the components of the carbon cycle—the atmosphere, terrestrial vegetation, soils, fresh water, lakes, and rivers, the ocean, and geological sediments are significant reservoirs of carbon. Capturing the movement of carbon, and hence feedbacks, between these reservoirs requires that individual component fluxes be known to comparable levels of uncertainty (see Appendix G, Figure G.1). Consequently, a number of geophysical parameters are needed to achieve this quantified objective: atmospheric CO_2 concentrations; land photosynthesis; ocean photosynthesis vegetation biomass, disturbance, and recovery; biomass burning; land respiration and decomposition; and the air-sea CO_2 exchange.

Understanding the carbon cycle feedback to the desired uncertainty level requires utilization and integration of a broad range of satellite and in situ observations, because all of these observations must be made at the same time to capture the movement of carbon accurately (see Table 4.4). In this example, only the geophysical variable "atmospheric CO_2 concentration" has a higher utility rating relative to the others, because this observation docu-

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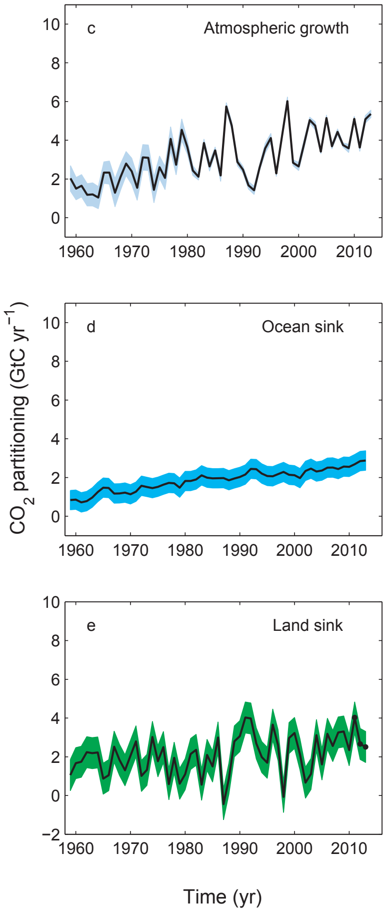

FIGURE 4.1 The three sinks of the global carbon budget and their uncertainties with time for (A) the atmosphere, (B) the ocean, and (C) the land. The shaded area is ±1σ. Only about half of total carbon emissions accumulate in the atmosphere with the balance divided between the ocean and land sinks. Note the high year-to-year variation in the land carbon sink while the year-to-year variation in the ocean carbon sink is roughly proportional to atmospheric ρCO_2. SOURCE: C. Le Quéré, R. Moriarty, R.M. Andrew, G.P. Peters, P. Ciais, P. Friedlingstein, S.D. Jones, et al., Global carbon budget 2014, *Earth System Science Data* 7:521-610, 2014.

ments the CO_2 concentration forcing in the atmosphere upon the climate system. The other carbon cycle geophysical variables are related to the sources and sinks of carbon that in aggregate result in the measured concentrations of atmospheric CO_2. Because of the multiple geophysical variables required, many of the individual observations related to the carbon cycle observations have low utility ratings.

The current system of atmospheric CO_2 measurements do not adequately constrain process-based carbon cycle models to allow diagnosis and/or attribution of the land and ocean carbon sinks and sources with any confidence—hence the models yield widely varying patterns of land and ocean sources and sinks. In addition, there must be a significant improvement in quantifying the global methane budget. The inability to reproduce an unambiguous picture of the current pattern of large-scale carbon fluxes and to discriminate the dominant mechanisms driving those patterns compromises scientists' ability to predict the future trajectory of the planetary carbon sinks and sources. In fact, current data sets are so sparse that systematic failures to capture important processes and their thresholds cannot be adequately diagnosed. Testing and improving the surface and ocean parameterizations in Earth system models that calculate the surface-atmosphere fluxes of energy, water, and carbon, is essential for developing the capability to predict future climate, but this has proved to be a challenging task.

To improve model parameterizations and reduce uncertainty in future projections, regional scale flux estimates of CO_2, at monthly time-scales and spatial scales of roughly ~1° × 1°, and with global coverage and over multiple annual cycles, are critical. For major urban areas, and for estimation of anthropogenic emissions, the flux determinations need to be at spatial scales on the order of 10 km.

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TABLE 4.4 Current Global Flux Uncertainty Levels for the Land Carbon Cycle and the Total Land Above Ground Carbon Pool for Comparison

	Current Fluxes and Uncertainty	
Carbon Cycle Component	Pg C	Atmospheric ppm CO_2 Equivalent per Year
Atmospheric CO_2 concentration	4.3 ± 2.1	2.0 ± 1
Land photosynthesis	123 ± 8	58 ± 3.8
Land vegetation biomass disturbance and biomass burning	0.9 ± 0.5	0.5 ± 0.4
Land carbon sink	2.9 ± 0.4	1.4 ± 0.2
Plant respiration	45 ± 9	21 ± 4.2
Soil[a] respiration—decomposition	75 ± 15	35 ± 7
Land vegetation above ground biomass—not a flux	450 ± 100	212 ± 47

[a] Roots, mycorrhizae, etc.

NOTE: The global land carbon sink is 2.9 ±0.8 Pg C yr^{-1} with a land cover change flux of 0.9 ±0.5 Pg C yr^{-1} (see Figure G.1). Currently the largest uncertainties are soil respiration/decomposition followed by plant respiration and land photosynthesis. Pg C is petagrams (10^{15} grams) of carbon; 1 ppm CO_2 (1 part per million by volume) is equal to 2.134 Pg C.

SOURCE: Data from Le Quéré et al. (2014), Schlesinger and Bernhardt (2013), Beer et al. (2010), and van der Werf et al. (2010).

These "top-down" flux products could be directly compared with "bottom-up" estimates of the fluxes generated from carbon cycle models forced by local environmental and remotely sensed data to precisely define the attribution of sink and sources, and thereby resolve model ambiguities. Carbon flux estimates with associated uncertainties will provide rigorous metrics for evaluating land and ocean process models, will help us in refining poorly understood model parameterizations, and will improve our predictive capability for the carbon climate system, supporting both basic geophysical understanding and policy-relevant applications.

As indicated in Table 4.4, soil respiration and soil decomposition are the fluxes whose uncertainty are of most consequence for improved understanding of the carbon cycle. To address these will require the linkage of in situ process studies with a variety of satellite data sources to determine how this important land carbon cycle component can be understood and modeled. A coordinated observing system will be required to execute and sustain a time series of global CO_2 atmospheric concentration and flux data products at spatial and temporal resolutions that allow rigorous evaluation and improvement of models needed to reduce uncertainty in future predictions/projections.

4.3 EVALUATING QUALITY

The quality characteristic is, along with affordability, the one most amenable to analytic analysis. As described in Section 3.6, quality might typically range from a value of 0 to 1, where 0 indicates that the measurement does not assist in achieving the science objective because quality is very low, and a value of 1, which indicates that the measurement fully meets the quantified objective (Table 4.5). The extremes of 0 and 1 are easy to understand; the challenge for this metric is to define logical partial fulfillment of the objective and provide a meaningful scale to judge the relative benefits of partial fulfillment. As noted in Chapter 2, while there are numerous ways to evaluate quality, a useful metric is expected to vary between continuity required for short-term operational use (weather prediction, agricultural crop monitoring, hazard warnings) versus for longer-term science objectives, such as those related to global change, including climate warming.

In the following subsections, the committee examines three different analytical approaches for evaluating quality.

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TABLE 4.5 Subjective Method Ratings for Quality (*Q*)

Rating for *Q*	Analytical Method Score (from Chapter 3)
0 - 0.2	Low
0.2 - 0.4	Moderate
0.4 - 0.6	High
0.6 - 0.8	Very high
0.8 - 1.0	Highest

4.3.1 Quality Example 1

A number of factors determine quality. One is whether the combined standard uncertainty of the measurement meets the quantified objectives. The instrument calibration uncertainty, repeatability, time and space sampling, and data systems and delivery for climate variables (algorithms, reprocessing, and availability) will determine the level of confidence that the measurement meets the objective. Assuming Gaussian statistics for measurement uncertainty, one can derive a metric for uncertainty assessment as follows. Let σ be the 1-sigma measurement uncertainty, r be the accuracy requirement of the objective (closeness of agreement between the result of the measurement and the value of the measurand), then

$$Q = \mathrm{P}(r/\sigma)$$

Where $\mathrm{P}(s)$ is the probability of a value within ± s for a normal distribution N(0,1). For example, if σ is 1/2 of the objective accuracy requirement, then $Q = 0.95$. If σ equals the accuracy requirement of the objective, then $Q = 0.68$.

The strength of this approach to a quality metric is its simplicity. The weakness is that it is not as closely coupled to the impact of changes in quality, such as the delay in time to detect climate trends (Section 4.3.2) or the ability to quantify the effect of a data gap.

4.3.2 Quality Example 2

Another factor in quality is the impact of a data gap on measurement repeatability and hence the tolerance of a gap in a measurement made with a given calibration uncertainty in addressing the quantified objective. The difference in quality of the climate record with and without continuity of the proposed measurement provides input for continuity decision making: If the difference in quality is small, the continuity observation priority will be low, if the quality difference is large, the continuity observation priority will be high.

The quality metric, *Q*, reflects the combined standard uncertainties of the existing and proposed continuity measurements in the context of a specified science objective. One approach for quantitatively estimating *Q* for climate records takes into account the length of a measurement record needed to achieve the required objective. This approach recognizes that higher quality observations (i.e., those with smaller calibration uncertainty and higher repeatability) provide scientific answers sooner, and that delayed knowledge can have corresponding societal consequences in delaying decision making. Leroy et al. (2008) establish equations relating observation uncertainty and time to detect climate change. Wielicki et al. (2013; Figure 3 and sidebars) discuss the uncertainty of a climate change observation relative to a perfect observing system limited by natural internal variability, and show the dependence of uncertainty on the length of measurement record.

Leroy et al. (2008) show that the time needed to achieve a measurement with an acceptable level of scientific uncertainty is:

$$\Delta t_P = \sqrt[3]{12 s^2 \sigma_{\mathrm{var}}^2 \tau_{\mathrm{var}} / m^2}$$

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where s is the signal-to-noise ratio such that $s = 2$ for a 95 percent confidence bound, m is the desired trend to measure in magnitude/year, σ^2 is the variance of natural variability, and τ_{var} is the autocorrelation time scale of natural variability. For the common AR-1 red noise statistical distribution, $\tau_{\mathrm{var}} = (1 + \rho)/(1 - \rho)$ (Weatherhead et al., 1998), where ρ is the lag-1 autocorrelation coefficient of the time series, commonly determined for global change records from annual mean time series to minimize noise from the seasonal cycle.[3]

"Perfect" means perfect instrument accuracy (i.e., small uncertainty and high repeatability), perfect sampling, and perfect algorithms (see Leroy et al., 2008, equation 11 with f = 0). Δt_P therefore defines the basic time scale of the scientific problem, and this differs for different problems. It defines the point of diminishing returns for advances that reduce measurement uncertainty and also establishes the minimum time investment for observations to achieve a measurement with the necessary fidelity.

In reality, no observing system is perfect. In actual observing systems, global change trends are subject to multiple uncertainties from factors discussed in the definition of continuity in Chapter 2: instrument calibration uncertainty, repeatability, time and space sampling, and data systems and delivery for climate variables (algorithms, reprocessing, and availability). The consequence of uncertainty in a measurement is that the time to detect a specified change is longer. A straightforward extension of Leroy et al. (2008) and Wielicki et al. (2013) defines the time to detect global change as

$$\Delta t = \sqrt[3]{12s^2\left(\sigma_{\mathrm{var}}^2\tau_{\mathrm{var}} + \sigma_{\mathrm{cal}}^2\tau_{\mathrm{cal}} + \sigma_{\mathrm{sam}}^2\tau_{\mathrm{sam}} + \sigma_{\mathrm{alg}}^2\tau_{\mathrm{alg}}\right)\Big/ m^2} \tag{1}$$

where the variance σ^2 and autocorrelation time scale τ for observation uncertainties are determined for calibration uncertainty (cal), taking into account both absolute calibration uncertainty and repeatability. If there are gaps in the record, the σ^2_{cal} term depends on instrument absolute calibration accuracy (uncertainty), but if continuity of the observation is preserved, σ^2_{cal} depends on the ability to prove instrument calibration stability (repeatability) taking into account the overlap intercalibration. In both cases, τ_{cal} is usually taken as a typical instrument lifetime (Leroy et al, 2008; Wielicki et al., 2013). The σ^2_{cal} and τ_{cal} terms, indicating the magnitude of the changing bias and the time scale for such changes, respectively, can also be considered measures of the lack of stationarity of the measurement. The σ^2_{cal} and τ_{cal} terms can also be considered measures of the lack of stationarity of the measurement: both the magnitude of the changing bias σ^2_{cal} as well as the time scale for such changes τ_{cal}. In the examples here, the worst case scenario is assumed, as done in Leroy et al. (2008), which accounts for either calibration drifts or gaps between measurements. Other valid approaches to this metric can be found in Weatherhead et al. (1998) that take into account the fraction of the data record with gaps as well as a certain or uncertain calibration change across a gap.

Time and space sampling (sam) uncertainties in satellite observations are dominated by orbital sampling and instrument design (e.g., nadir only versus swath scan), and the σ^2_{sam} may be determined using orbital sampling simulations, with τ_{sam} determined by the time-averaging interval for the global change time series, typically annual mean values. Algorithm uncertainty (alg) in climate trends is primarily the (in)stability of a retrieval algorithm when applied to climate change observations, including issues of changing instrument design (e.g., spectral bandpass) over time. For natural variability (var), exclusive of the anthropogenic trend, the σ^2_{var} and τ_{var} terms are determined using past observations as well as estimated using Earth system model simulations (see Leroy et al., 2008; and Wielicki et al., 2013, for examples).

The increase in the time to detect global change thus depends fundamentally on the magnitude of observational uncertainty and repeatability as compared to natural variability. For example, it can be shown (Wielicki et al., 2013) that the time to detect ratio is

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[3] For climate records, the time series used to determine natural variability will typically be either deseasonalized monthly or annual average series. For monthly time series, the variance will be higher, but autocorrelation time smaller than for annual mean time series. The final result of the time to detect trends tends to be insensitive to this choice (Phojanamongkolkij et al., 2014).

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$$X = {\Delta t}\big/{\Delta t_P} = \sqrt[3]{1 + \left(\sigma_{\text{cal}}^2 \tau_{\text{cal}} + \sigma_{\text{sam}}^2 \tau_{\text{sam}} + \sigma_{\text{alg}}^2 \tau_{\text{alg}}\right)\big/\sigma_{\text{var}}^2 \tau_{\text{var}}} \qquad (2)$$

To quantitatively assess how measurement continuity influences the quality of a measurement record, the time to detect global change (at the corresponding time to detect ratios, relative to a perfect observing system) can be specified for the measurement record with continuity, Δt^C, and without continuity, Δt^{NC}.

Conceptually, the objective for a continuity decision is to evaluate the societal and scientific impact of measurements with and without continuity. A quality metric that distinguishes between these two options should therefore exhibit:

- *Higher ratings* for measurements that are more certain and, therefore, achieve the quantified objective in a shorter time, thereby providing climate change societal information in a shorter time; and
- *Lower ratings* for measurements that are less certain and, therefore, delay achievement of the quantified objective thereby delaying societal benefits. The reduced certainty may arise from poor accuracy, data gaps, poor repeatability, large sampling or algorithm uncertainty.

To be effective in the proposed framework, a quality metric should be simply related to the proposed measurement's delay in the time to detect trends $\Delta t - \Delta t_P$ with respect to a perfect observing system while providing the 0 to 1 quality metric desired for the framework in Chapter 3. An observation with 0 years of delay would therefore receive a Q score of 1.0, while a measurement with a long delay (e.g., 30 years or longer) would receive a Q score of 0.0. A delay of 30 years would be considered a very long delay for both science as well as societal uses. This is especially true for climate data records, given the urgency to narrow uncertainty in climate projections for the 21st century. An example of such a simple Q metric is given by:

$$\begin{array}{ll} Q_2 = 1 - (\Delta t - \Delta t_P)/30 & \text{for } Q > 0, \\ Q_2 = 0 & \text{for } Q < 0 \text{ (i.e., delay longer than 30 years)} \end{array} \qquad (3)$$

Table 4.6 shows the relationship in Equation 3 between Q_2 and the time delay of trend detection. The Q_2 metric in Equation 3 has the advantage of both simplicity and the ability to adjust the maximum time delay (30 years in the example) to any value deemed appropriate for the decision process. For use in the decision framework for continuity, Q_2 would be evaluated for any of the observation options being considered. Appendix B provides examples of estimations of this Q_2 metric both with and without continuity for a range of climate data records.

Because the use of $\Delta t - \Delta t_P$ in the Q_2 metric depends modestly on the value of the trend m required for the quantified objective, there is a link between a climate record objective and the Q_2 quality metric.[4] Gaps in a climate record will affect the Q_2 metric by increasing the time to detect trends. Examples of the impact of gaps on climate trend detection can be found for TSI (NRC, 2013) and for cloud feedback (Loeb et al., 2009). Reduced time to detect trends is closely related to reduced uncertainty in trends (Weatherhead et al., 1998; Leroy et al., 2008; Wielicki et al., 2013). The later metric is useful for understanding the constraints of uncertainty in climate models (see the example in Appendix C).

A less prescriptive approach might evaluate quality by directly assessing the repeatability and length of the extant measurements record for which continuity is being proposed, relative to the objectives, taking into account the required uncertainty of the detection; for example, to within 1*s*, 2*s*, or 3*s*. In this case, higher Q values reflect

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[4] If the quantified objective is only capable of detection of very large trends, then its importance may decrease relative to an objective with the capability to detect smaller trends that require higher accuracy to detect. The climate sensitivity example in Appendix C provides such a case: if only very large trends in cloud feedback can be observed, then the uncertainty in cloud feedback is not reduced significantly (see Figure C.1 in Appendix C). If much smaller cloud feedback trends can be observed, then the uncertainty in climate feedback can be reduced significantly. This selection through the objective changes the value of m in (1), which in turn determines the quality of the observation required to meet the more challenging but more important objective. Similar logic would apply to the other objective examples in the appendixes for sea level rise, changing ocean heat storage, changing ice sheet mass balance, and global land carbon sinks.

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TABLE 4.6 Example of the Dependence of the Quality Metric Q_2 for a Proposed Measurement on the Time Delay for Its Measurement of Climate Trends When Compared to the Time to Detect the Trend for a Perfect Observing System

Time Delay $\Delta t - \Delta t_P$ (years)	Q_2
0	1.0
5	0.83
10	0.67
15	0.50
20	0.33
25	0.16
30	0

a measurement with sufficient repeatability to achieve an objective with greater than 95 percent confidence (i.e., within 2s uncertainty), and lower Q values correspond to those with less than 68 percent confidence.

> **Finding: The quality of a measurement may be quantitatively evaluated by combining metrics arising from instrument calibration uncertainty, repeatability, time and space sampling, and data systems and delivery for climate variables (algorithms, reprocessing, and availability). Measurements that suffer the largest reduction in quality from a gap in observations have higher priority for continuity.**

4.4 EVALUATING SUCCESS PROBABILITY

The success probability (*S*) is defined as the probability that the proposed observation will successfully meet the goal of continuing the extant record, as proposed. This should account for the observation's resilience to gaps, the possibility of leveraging international partnerships, international redundant observations, or other types of leverage. It also captures issues that would affect the ability of the proposed observation to meet the scientific or societal goal, to the extent that they do not appear via the cost of the measurement. Thus, one definition of the probability of success (*S*) is

$$P_s = P_{\text{accu}} P_{\text{sam}} P_{\text{alg}} (1 - P_{\text{gap}}) P_{\text{mgt}}$$

where P_{accu}, P_{sam}, and P_{alg} are treated as independent variables[5] that define the success likelihood of achieving the instrument's long-term accuracy (P_{accu}; through calibration and repeatability), sampling (P_{sam}), and algorithm (P_{alg}) requirements used in the determination of the quality metric for a proposed observation.

P_{gap} defines the likelihood of an impactful gap occurring given the proposed observation strategy. This gap probability depends on the extent of required overlap between successive instruments, the number of instruments in orbit, their age, their design life, the spacecraft design life, and the launch date of the next continuity observation (Loeb et al., 2009). If the calibration uncertainty in the quality metric is sufficiently low to avoid the need for data overlap to achieve the quality metric, then P_{gap} is set equal to 0, because short record gaps have little effect

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[5] Not independent variables in a strictly statistical sense; instead, these are factors in determining the overall success of achieving a quantified objective. The factors are in fact independent physical concepts: accuracy, sampling, algorithm, gap probability, and management risk. While it is correct that there are statistics involved in the individual components, the reason these probabilities are multiplied is not because they are independent, but instead because any one of them can cause failure to achieve the objective.

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on global change detection.[6] Finally, P_{mgt} is the probability that the mission will be successfully managed and carried out as planned. Values for P_{mgt} will vary according to whether the mission is implemented in a Class B, C, or D modes, with increasing probabilities going from Class D to B.[7]

Recognizing the challenges with quantifying P_{accu}, P_{sam}, P_{alg}, P_{gap}, and P_{mgt}, a more qualitative evaluation scale can be developed to support a benefit analysis. An example of such a scale is shown in Table 4.7; the committee emphasizes that this scale is presented for illustrative purposes and that NASA may wish to develop its own. As with the other characteristics of the framework, the calculation of success probability in the committee's notional scheme requires subjective inputs; however, these inputs appear transparently.

Application of the above scoring approach to the quantified objective/measurement examples given in the appendixes yields the success probabilities in Table 4.8.

4.5 EVALUATING AFFORDABILITY

Affordability should be judged as the cost per year of continuing the prescribed measurement for a specified time period with the required quality, relative to the total budget that NASA has allocated for all its satellite measurements.

To achieve the required quality, the measurement must have the uncertainty, repeatability, time and space coverage, and reduction algorithms to meet the scientific requirements. The cost is, therefore, the full funding needed to make the observations and produce the measurement for a finite length of time: it includes space platform accommodation, launch, validation, algorithm implementation, and science team contributions. Should multiple overlapping observations be prescribed to preclude gaps and achieve the needed repeatability of the measurement over the specified time, they are also part of the cost. Included as well are additional factors that reduce risk, such as advancing the instrument technology readiness level (TRL) and auxiliary measurements, should they be needed, to implement the algorithms that produce geophysical quantities. To the extent that factors such as TRL, gap mitigation, validation and algorithm maturity development are included in the measurement cost, they may enhance the associated success probability of the measurement. Thus cost shares a number of cross cutting characteristics with utility, quality, and success probability that must be quantified and implemented in the value metric.

As discussed in Section 3.6 regarding the quantitative cost-benefit type evaluation, the relative weights given to the affordability and importance factors determine the relative weighting between affordability and benefit. If, for instance, the evaluation scale for importance is comprised of five levels (e.g., Table 3.1), then a similar scale for affordability would be needed to achieve equal weighting. Table 4.9 is an example of such a scale.

4.6 SUMMARY EVALUATION OF THE FRAMEWORK CHARACTERISTICS

As described in Section 3.6, the committee has focused on two approaches for evaluation of the framework measurement characteristics, namely, subjective and analytical methods. For the subjective method, an expert-based adjectival rating for each of five measurement characteristics constitutes the input to the summary evaluation. The final value rating (V) reflects an average, or weighted-average, of the five individual characteristic evaluations. For the analytical approach, value would be calculated according to the formula given in Section 3.6 (i.e., $V = I \times U \times Q \times S \times A$), based on numerical ratings of the characteristics as described in the above subsections. Table 4.10 compares the two methods.

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[6] In Section 4.4, the committee addresses gaps from the perspective of the success probability characteristic. The effect of gaps on the quality metric is discussed in Section 3.4.2 and in Appendixes B and C. Appendix C also provides references on the analysis of gap risk of occurrence for top of the atmosphere radiation budget observations. The effect of gaps on repeatability is reviewed in Chapter 2 as part of the discussion on the measurement of total solar irradiance (TSI) and the recent report on continuity for TSI measurements (NRC, 2013) also considers gap likelihood of occurrence. Finally, an extensive discussion of methods to calculate the probability of a gap for satellite observations can be found in Loeb et al. (2009).

[7] See NASA, NASA Procedural Requirements, NPR 8705.4, *Risk Classification for NASA Payloads*, Washington, D.C., 2004, http://nodis3.gsfc.nasa.gov/npg_img/N_PR_8705_0004_/N_PR_8705_0004_.pdf; and K.W. Ledbetter, "Science Mission Directorate Implementation of Spacecraft Risk Classifications," July 6, 2006, http://science.nasa.gov/media/medialibrary/2010/03/31/Gen_Jul06_LedbetterPresentation_.pdf.

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TABLE 4.7 Subjective Method Ratings for Success Probability (*S*)

Rating for *S*	Analytical Method Score (from Chapter 3)	Scoring Rationale
0 - 0.2	Low	Instrument performance (including instrument calibration uncertainty, repeatability, time and space sampling, and data systems and delivery of climate variables [algorithms, reprocessing, and availability]) has either experienced previous on-orbit degradation or is not well established by traceability to a space-proven design or characterization in a laboratory or airborne environment. Accordingly, degradation of instrument performance and impactful record gaps are likely and would substantially impact record quality. Few or no redundant capabilities exist (or are planned) outside of NASA to support maintenance of the record quality.
0.2 - 0.4	Moderate	Instrument performance has either experienced previous on-orbit degradation or is not well established by traceability to a space-proven design or characterization in a laboratory or airborne environment. Accordingly, degradation of instrument performance and impactful record gaps are likely and would substantially degrade record quality. Some redundant/complementary capabilities exist (or are planned) outside of NASA that can support maintenance of the record quality.
0.4 - 0.6	High	Some elements of instrument performance have been established by traceability to a space-proven design or characterization in a laboratory or airborne environment. Impacts on data quality due to instrument performance degradation are mitigated by instrument performance margin. Only short record gaps are likely with limited capability to impact the data record quality. Some redundant/complementary capabilities exist (or are planned) outside of NASA that can support maintenance of the record quality.
0.6 - 0.8	Very high	Most elements of instrument performance have been established by traceability to a space-proven design or characterization in a laboratory or airborne environment. Impacts on data quality due to instrument performance degradation are mitigated by instrument performance margin. Only short record gaps are likely with limited capability to impact the data record quality. Significant redundant/complementary capabilities exist (or are planned) outside of NASA that can support maintenance of the record quality.
0.8 - 1.0	Highest	Long-term instrument performance is well established. Expected degradation of instrument performance is well within required quality thresholds. Impactful record gaps are unlikely given that overlapping instrument records are not required and substantial redundant/complementary capabilities exist (or are planned) outside of NASA that can support maintenance of the record quality.

To illustrate the application of these methods, the committee evaluated benefit for some example measurements related to the quantified objectives listed in Box 3.2 (see Table 4.11). For these examples, the objectives were not differentiated with respect to importance (all measurements given ratings of "highest" and scores of 5). Also, the examples were confined to evaluation of benefit due to the lack of sufficient, readily available, cost information needed to quantitatively establish affordability. Illustrative examples of the benefit evaluations are given in the appendixes.

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TABLE 4.8 Example Calculations of Measurement/Instrument Success Probabilities

Measurement/ Instrument	Quantified Objective	P_s (*S*)	Scoring Rationale
MODIS/VIIRS	Climate Sensitivity (see Appendix C)	1.0	On-orbit experience
CERES+MODIS/VIIRS		0.9	Sensitive to CERES data gaps
CLARREO+ CERES+MODIS/ VIIRS		0.8	No on-orbit experience for CLARREO
Radar altimetry	Sea Level (see Appendix D)	1.0	On-orbit experience
Gravity		1.0	On-orbit experience
Radar altimetry + gravity	Ocean Heat (see Appendix E)	1.0	On-orbit experience
Laser altimetry	Ice Sheet Mass (see Appendix F)	0.8	Novel photon-counting technology for the lidar
Gravity		1.0	On-orbit experience
InSAR		0.8	On-orbit SAR experience
CO_2 concentration	Land Carbon (see Appendix G)	0.95	Initial OCO-2 experience
Land photosynthesis		0.9	On-orbit experience MODIS/VIIRS
Land biomass and change		0.8	On-orbit experience Landsat. No on-orbit experience for laser altimetry or radar sensing of volume.
Biomass burning		0.95	On-orbit experience MODIS/VIIRS and Landsat
Respiration/decomposition		0.8	Requires in situ process studies linked to OCO-2, Landsat, MODIS/VIIRS, and SMAP

NOTE: CERES, Clouds and Earth's Radiant Energy System; CLARREO, Climate Absolute Radiance and Refractivity Observatory; InSAR, interferometric synthetic aperture radar; MODIS, Moderate-Resolution Imaging Spectroradiometer; OCO-2, Orbiting Carbon Observatory-2; SMAP, Soil Moisture Active-Passive; VIIRS, Visible Infrared Imaging Radiometer Suite.

TABLE 4.9 Subjective Method Ratings for Affordability (*A*)

Rating for *A*	Analytical Method Score (from Chapter 3)	Scoring Rationale—Total Cost as a Percentage of Total Available NASA Funds
1	Low	>80%[a]
2	Moderate	Between 60 and 80%
3	High	Between 40 and 60%
4	Very high	Between 20 and 40%
5	Highest	<20%

[a] Should international partners or leveraging opportunities exist, they would be reflected in a lower cost to NASA.

TABLE 4.10 Comparison of Summary Evaluation Methods

Evaluation Metric	Subjective Method Ratings	Analytical Method Scores (from Chapter 3)
Importance (*I*)	Low, Moderate, High, Very High, Highest	1 - 5
Utility (*U*)	Low, Moderate, High, Very High, Highest	0 - 1
Quality (*Q*)	Low, Moderate, High, Very High, Highest	0 - 1
Success Probability (*S*)	Low, Moderate, High, Very High, Highest	0 - 1
Affordability (*A*)	Low, Moderate, High, Very High, Highest	1 - 5
Overall Value (*V*)	**Poor, Fair, Good, Very Good, Excellent**	**0 - 25**

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TABLE 4.11 Overall Benefit Evaluations for Example Measurements Related to Quantified Objectives Given in Box 3.1

Quantified Objective	Measurement[a]	Subjective Benefit Rating	Analytical Benefit Score (*B*)
Equilibrium Climate Sensitivity	MODIS/VIIRS	Poor	0.5
	CERES/MODIS/VIIRS	Good	2.2
	CLARREO/CERES/MODIS/VIIRS	Very Good	4.0
Sea Level Rise Acceleration	Jason	Excellent	5.0
	GRACE	Very Good	4.0
CO_2 Concentration	OCO-2	Excellent	4.5
Land Photosynthesis	MODIS-VIIRS, OCO-2	Good	4.3
Land Biomass & Change	MODIS-VIIRS, Landsat	Good	3.2
Biomass Burning			
Respiration & Decomposition	MODIS-VIIRS, Landsat, OCO-2	Excellent	4.5
	MODIS-VIIRS, SMAP, OCO-2	Fair	1.0
Ocean Heat Storage Change	GRACE + Jason	Good	3.4
Ice Sheet Mass Balance Change	ICESat + OIB	Fair	2.4
	GRACE	Very Good	4.5
	NISAR	Good	3.6

[a] Some of the table entries use mission names as a generic representation of a measurement; thus, for example, the entry "GRACE" indicates current or future measurements of Earth's time- and spatially varying gravity field; "Jason" refers to current and future precision measurements of ocean surface topography; "ICESat" refers to continuation of benchmark elevation measurements that can be related to ice sheet mass balance; and "Landsat" refers to current (Landsat-8) and future implementations of a moderate resolution, multispectral land imager. In some cases, a mission name indicates an anticipated future measurement capability; for example, CLARREO refers to the development of a suite of climate benchmarking measurements described in the 2007 NRC decadal survey (NRC, 2007).

NOTE: CERES, Clouds and Earth's Radiant Energy System; CLARREO, Climate Absolute Radiance and Refractivity Observatory; GRACE, Gravity Recovery and Climate Experiment; ICESat, Ice, Cloud, and land Elevation Satellite; InSAR, interferometric synthetic aperture radar; MODIS, Moderate-Resolution Imaging Spectroradiometer; NISAR, NASA-ISRO synthetic aperture radar; OCO-2, Orbiting Carbon Observatory-2; OIB, Operation IceBridge; SMAP, Soil Moisture Active-Passive; VIIRS, Visible Infrared Imaging Radiometer Suite.

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Appendixes

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A

Statement of Task

An ad hoc committee will develop a framework to assist NASA's Earth Science Division (ESD) in their determinations of when a measurement(s) or data set(s) should be collected for durations longer than the typical lifetimes of single satellite missions. Although focused on the particular needs of NASA's Earth Science Division, the committee will consider the relevant current and planned Earth observation programs of NOAA and the USGS. In addition, the committee will review existing NASA policy regarding the scope of its Earth Science Program; the 2007 NRC decadal survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*; and the 2010 NASA report, *Responding to the Challenge of Climate and Environment Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space*.

The committee will seek to provide guidance to NASA that will be broadly applicable under a variety of scenarios that might unfold over decadal timeframes. In particular, and considering the expected constrained budgets for the NASA earth science program, the committee will:

1. Provide working definitions of, and describe the roles for "continuity" for the measurements and data sets ESD initiates and uses to accomplish Earth system science objectives;
2. Establish methodologies and/or metrics that can be used by NASA to inform strategic programmatic decisions regarding the scope and design of its observation and processing systems:
   a. In the context of limited resources and recognizing the programmatic and fiscal tension between the scientific benefits of providing sustained measurements on the one hand, and developing and demonstrating new or improved measurements on the other hand, determine whether a measurement(s) should be collected for extended periods, and provide guidance concerning methods to determine the appropriate balance between cost, risk, and performance when addressing continuity needs for specific measurements; and
   b. Prioritize the relative importance of measurements that are to be collected for extended periods;
   c. Identify the characteristics of, and extent to which, data gaps and/or accuracy/sampling/stability degradations are acceptable for existing and planned data sets;
3. In addition, where appropriate in addressing the Statement of Task, the committee may:
   a. Examine other means for achieving effective continuity such as alternative, non-space-based instrument platforms;

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b. Examine the potential enhancements or degradations in the scientific utility of information products that might result from combining multiple measurement sources (versus single-mission or single-instrument information products); and,
c. Provide illustrations of how the proposed framework might be applied to evaluate either the present NASA-ESD Climate-Centric Architecture, or used in the creation of recommendations for the upcoming decadal survey in Earth science and applications from space.

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B

Quality Metric Examples Using Current Climate Data Records

Chapter 4, Section 4.3.2, defines a method to quantify the quality of a climate record by the time required to detect climate change trends. The time to detect trends decreases as quality increases, thereby increasing the science value and societal value of the observation. This appendix applies the equations defined in Section 4.3.2 to a range of current climate data records to demonstrate examples of the quality metric Q_2, both with and without continuity (Table B.1). Appendix C is also an example of applying the Q metric to a full quantified objective example, but for the shortwave cloud forcing data record.

Many climate data records (surface or satellite) have multiple versions usually developed and analyzed by different research groups. For the quality metric examples shown below the primary quantity controlling the time to detect climate change is the natural variability level in the record and its magnitude relative to long term trends, and to uncertainty analysis of the climate record. Interannual to decade scale natural variability tends to be large for most climate records and the differences in climate data records do not significantly change the natural variability estimate from the record. Examples of this are shown in Figure B.3 for two versions of middle tropospheric temperature, and Figure B.2 for global total ozone. For such cases, the Q metric tends to depend minimally on the climate data record version used.

The climate records analyzed are shown in Figures B.1 to B.4; each is a time series of annual average values, with the time unit in years. For all cases the confidence internal is 95 percent ($s = 2$) and the length of the satellite mission is 10 years ($\tau_{unc} = 10$). The selection of $s = 2$ for the confidence interval is arbitrary and is made for purpose of illustration; the value of s will likely vary depending on the significance of the trend and the required accuracy for testing key climate change hypotheses. Except for total solar irradiance (TSI), for which directly measured TSI observations are used, the quantities are evaluated using deseasonalized anomalies obtained by removing the annually repeating seasonal variations. Long-term trends are estimated statistically, by fitting a line (Figure B.1), polynomial (Figure B.4) or from multiple regression analysis of the measurements (Figures B.2 and B.3; Lean, 2014).

The trends shown in the figures have two-fold importance: firstly, they allow direct comparisons of different versions of a climate data record, whereby trend differences quantify the (lack of) repeatability, and secondly the removal of the trend quantifies the (residual) “natural” variability of the measurement, against which the trend magnitude is then compared. The upper panels in Figures B.1-B.4 show the annual mean (deseasonalized in Figures B.2 to B.4) climate data records, including their trends (green lines), and the lower panels show the residual “natural” variability obtained by removing the trends from the deasonalized annual mean values. Note that detecting

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TABLE B.1 Existing Climate Records and Estimated Parameters for their Quality Expressions

Climate Record	Total Solar Irradiance	Global Total Ozone Anomaly	Microwave Sounding Unit Mid-troposphere Global Temperature Anomaly	Arctic Sea Ice Area	Global Sea Level Anomaly
nominal	1361.5 W m^{-1}	294 DU	−17.5°C	12 ´ 10^6 km^2	0 mm
L	35 years	35 years	35 years	35 years	23 years
m	0.015 W m^{-2} yr^{-1}	0.1 DU yr^{-1}	0.01°C yr^{-1}	0.3 ´ 10^6 km^2 yr^{-1}	1 mm yr^{-1}
σ_{unc}	0.5 W m^{-2}	3 DU	0.2°C	0.5 ´ 10^6 km^2	0.4 mm yr^{-1}
σ_{rep}	0.02 W m^{-2} yr^{-1}	0.3 DU yr^{-1}	0.01°C yr^{-1}	0.01 ´ 10^6 km^2 yr^{-1}	2 mm yr^{-1}
τ_{unc}, τ_{rep}	10	10	10	10	10
σ_{var}	0.5 W m^{-2}	2.5 DU	0.14°C	0.17 ´ 10^6 km^2 yr^{-1}	2.3 mm
τ_{var}	8	2	1	1.4	2
Δt_P	75.2 years	39.1 yrs	21.1 years	2.8 years	8.0 years
Δt^C	75.3 years	40.1 years	21.5 years	2.8 years	8.56 years
Δt^{NC}	98.6 years	78.9 years	58.6 years	11.1 years	17.6 years
X^C	1.001	1.023	1.017	1.008	1.05
X^{NC}	1.3	2.0	2.8	4.0	2.2
Q_2 with continuity	1.00	0.97	0.99	1.00	0.98
Q_2 without continuity	0.22	0.00	0.00	0.72	0.68

NOTE:
L is the length of the currently available satellite climate record used to provide the examples in Appendix B.
m is the magnitude of the climate trend detection level required to meet the quantified objective
σ_{unc} is the instrument calibration uncertainty relative to international physical standards.
σ_{rep} is the instrument repeatability (often called stability).
τ_{unc}, τ_{rep} are the time scales of typical instrument lifetime in orbit.
σ_{var} is the standard deviation of climate system natural variability.
τ_{var} is the time scale of climate system natural variability.
Δt_P is the time scale to detect a trend of magnitude m at 95% confidence for a perfect observing system (zero uncertainty in the observation, limited only by natural variability).
Δt^C is the time scale to detect a trend of magnitude m at 95% confidence for an observing system with calibration uncertainties of σ_{unc}, σ_{rep}, τ_{unc}, τ_{rep} that achieves continuity of the observations.
Δt^{NC} is the time scale to detect a trend of magnitude m at 95% confidence for an observing system with calibration uncertainties of σ_{unc}, σ_{rep}, τ_{unc}, τ_{rep} that *fails* to achieve continuity of the observations.
X^C is the ratio of $\Delta t^C/\Delta t_P$ and provides the fractional increase in time to observe a climate system trend using an observing system *with continuity* relative to that of a perfect observing system. Note that X^C is independent of the assumed value of m.
X^{NC} is analogous to X^C, but for an observing system *without continuity.*
Q_2 is an example quality metric (Eq. 3 of Section 4.3.2) that converts delay in the time to detect climate trends versus a perfect observing system ($\Delta t - \Delta t_P$) into a quality metric scale of 0 to 1 for use in the value framework.

such trends as shown in the upper panels of the figures is a scientific objective of the measurements. The statistical metrics of the residual "natural" variability given in the lower panels of the figures are directly incorporated into the quality metric: the square of the standard deviation of the residuals (given by sdev in the figures) provides an estimate of the variance, $\sigma_{var}{}^2$, in Equation 1 and the autocorrelation at the first (1 year) lag (given by acf1 in the figures) allows for estimation of the autocorrelation time scale τ_{var} = (1 + acf1)/(1 - acf1).

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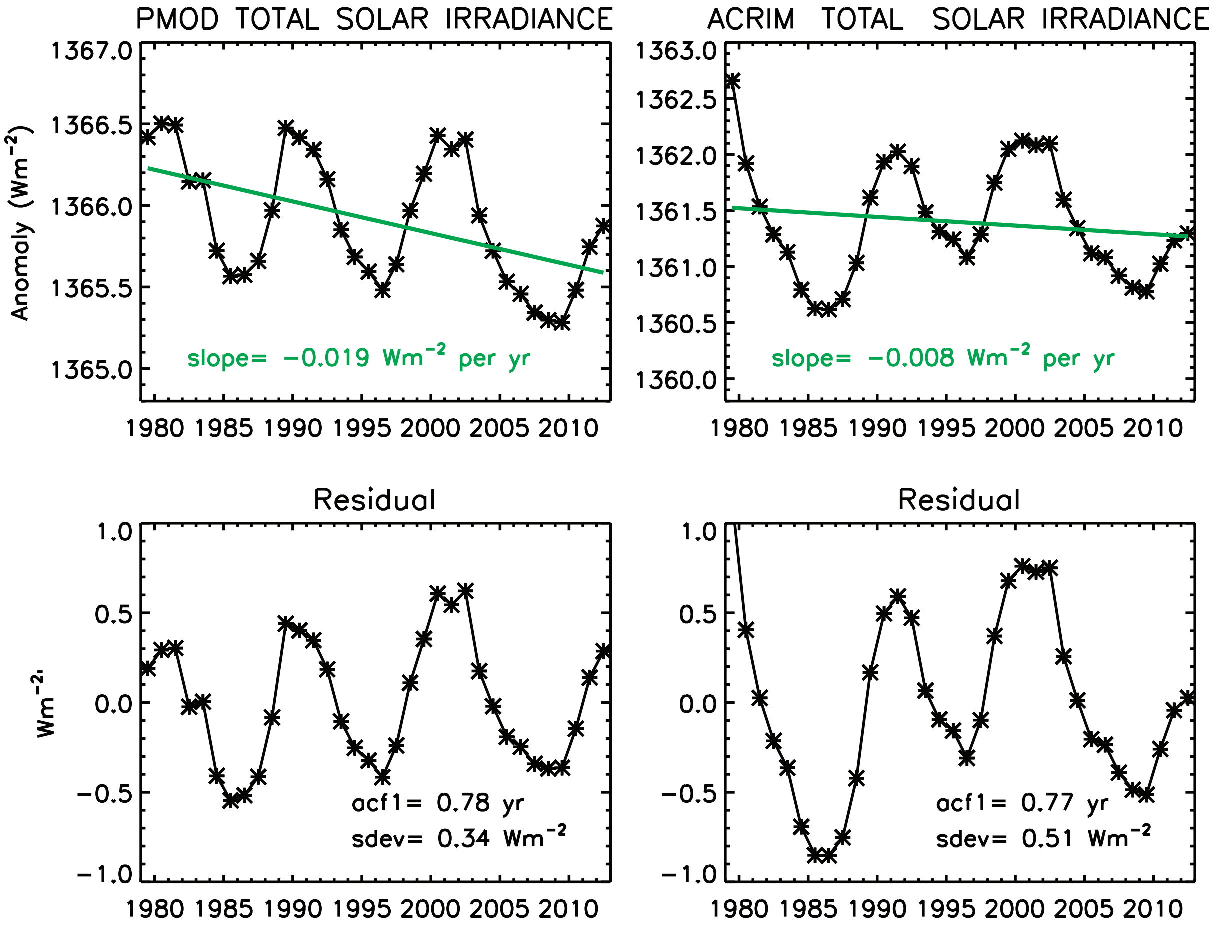

FIGURE B.1 Total solar irradiance. Shown in the top panels are annual mean values of total solar irradiance according to two different composite records, PMOD (Physikalisch-Meteorologisches Observatorium Davos) and ACRIM (Active Cavity Radiometer Irradiance Monitor), each constructed using different combinations of individual observations (from the total solar irradiance [TSI] database show in Chapter 2), and corrections for bias calibration and drift. The lines, which are linear fits to the annual mean values, have different slopes which indicate that the repeatability of the 35-year TSI record is no better than 0.01 W m^{-2} per year. Shown in the bottom panels are the residuals of the two time series in the upper panel from the linear trends, which indicate "natural" TSI solar cycle variations in the two records. That the 1σ values of the residuals (given by sdev in the figures) of the PMOD and ACRIM composites differ, indicates disagreement in their respective characterizations of the 11-year solar cycle signal, against which possible long-term irradiance trends must be detected. SOURCE: Courtesy of Judith L. Lean, Naval Research Laboratory.

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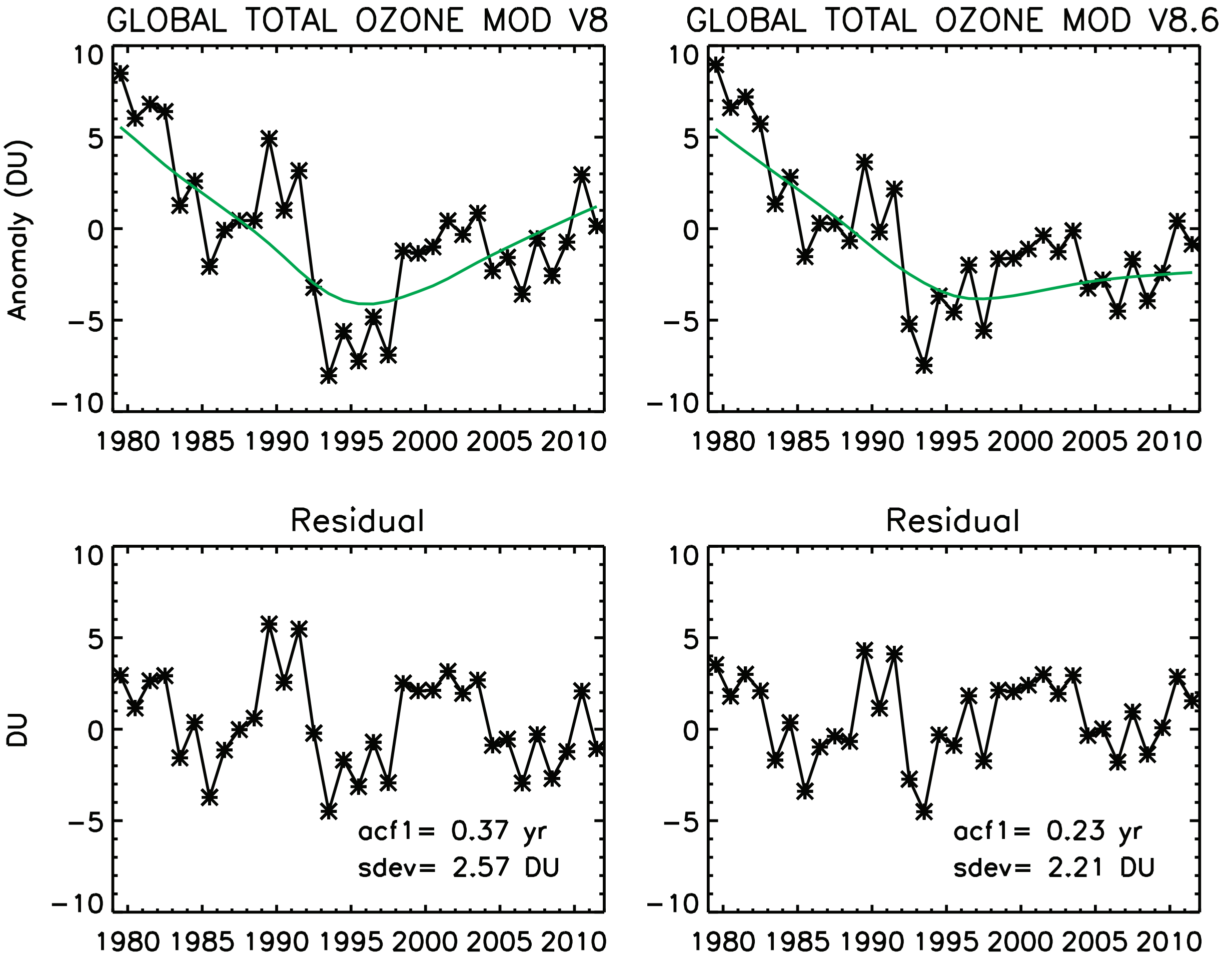

FIGURE B.2 Global total ozone. Shown in the upper panels are annual mean values of global total ozone anomalies (deseasonalized by removing an average annual cycle) according to two different composite records, MOD V8 and MOD V8.8, constructed from, respectively, the TOMS (Total Ozone Mapping Spectrometer) and SBUV (Solar Backscatter UltraViolet) observations, with different techniques for assessing long-term changes in each of multiple instruments flown on a sequence of satellites. The smooth curves through the annual mean values are estimates of the combined influence of anthropogenic chlorofluorcarbons and greenhouse gases, derived from statistical regression models of the monthly ozone data sets (Lean, 2014). The residuals of the annual global total ozone from the trends, shown in the bottom panel, are indicative of "natural" variability in ozone, due to various influences, including solar irradiance changes, volcanic eruptions, and the Quasi-Biennial Oscillation. The magnitude of this variability, estimated by the 1σ standard deviations of the residuals (given by sdev in the figures), indicates the "noise" of ozone natural variability, against which anthropogenic changes, including ozone recovery following the Montreal Protocol must be detected. SOURCE: Courtesy of Judith L. Lean, Naval Research Laboratory.

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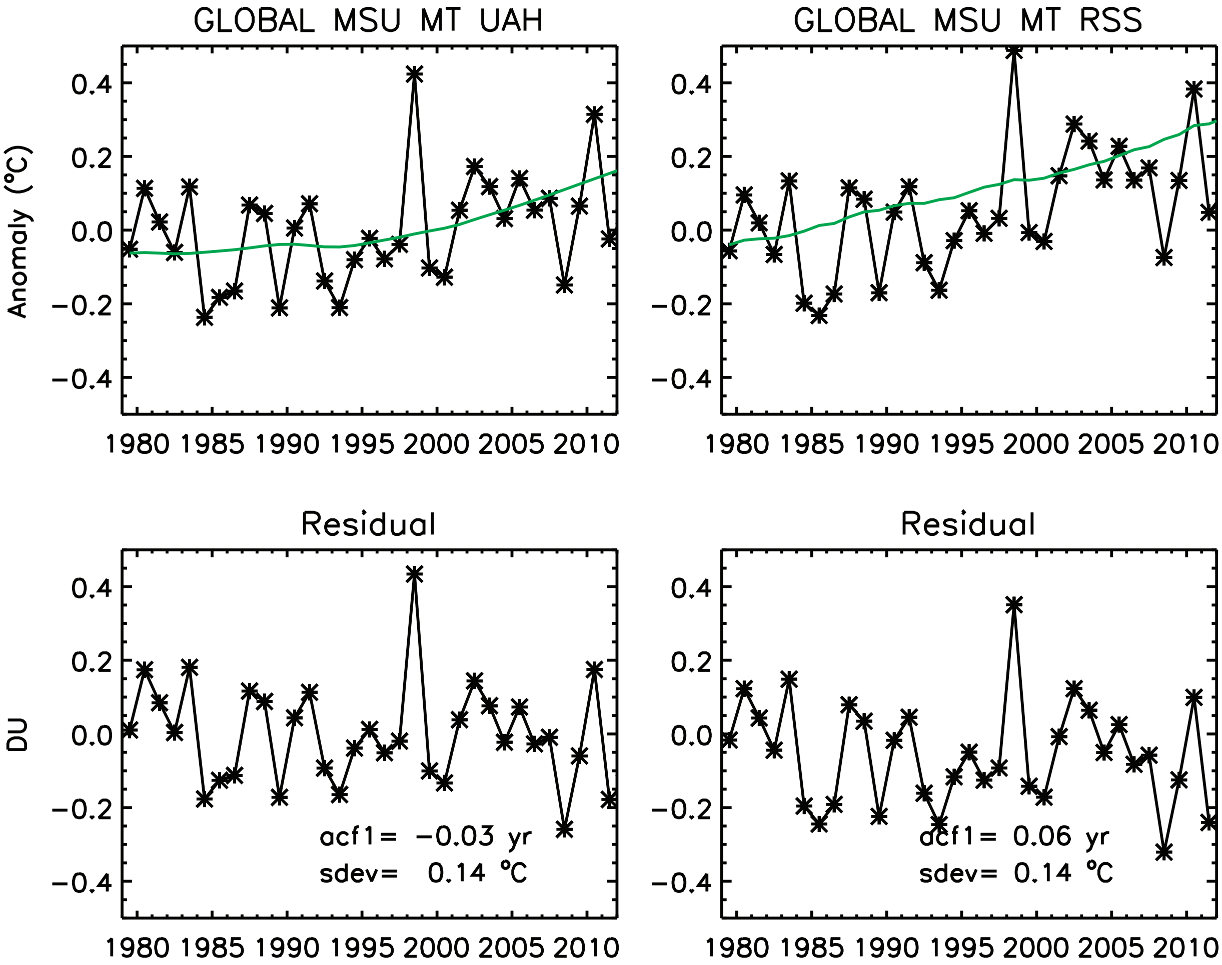

FIGURE B.3 Global middle troposphere temperature. Shown in the top panel are annual mean values of global middle troposphere temperature anomalies (at about 5 km, deseasonalized by removing an average annual cycle), according to two different analyses of observations made by a series of MSU/AMSU (Microwave Sounding Unit/Advanced Microwave Sounding Unit) instruments flown on a sequence of satellites (as discussed in Chapter 2). The smooth curves through the annual mean values are estimates of the trends. The residuals of the annual global middle troposphere temperature from the trends, shown in the bottom panel, are indicative of "natural" variability due to various influences including solar irradiance changes, volcanic eruptions and El Niño southern oscillation. The magnitude of this variability, estimated by the 1σ standard deviations of the residuals (given by sdev in the figures), indicates the "noise" of middle troposphere natural variability, against which anthropogenic changes must be detected. SOURCE: Courtesy of Judith L. Lean, Naval Research Laboratory.

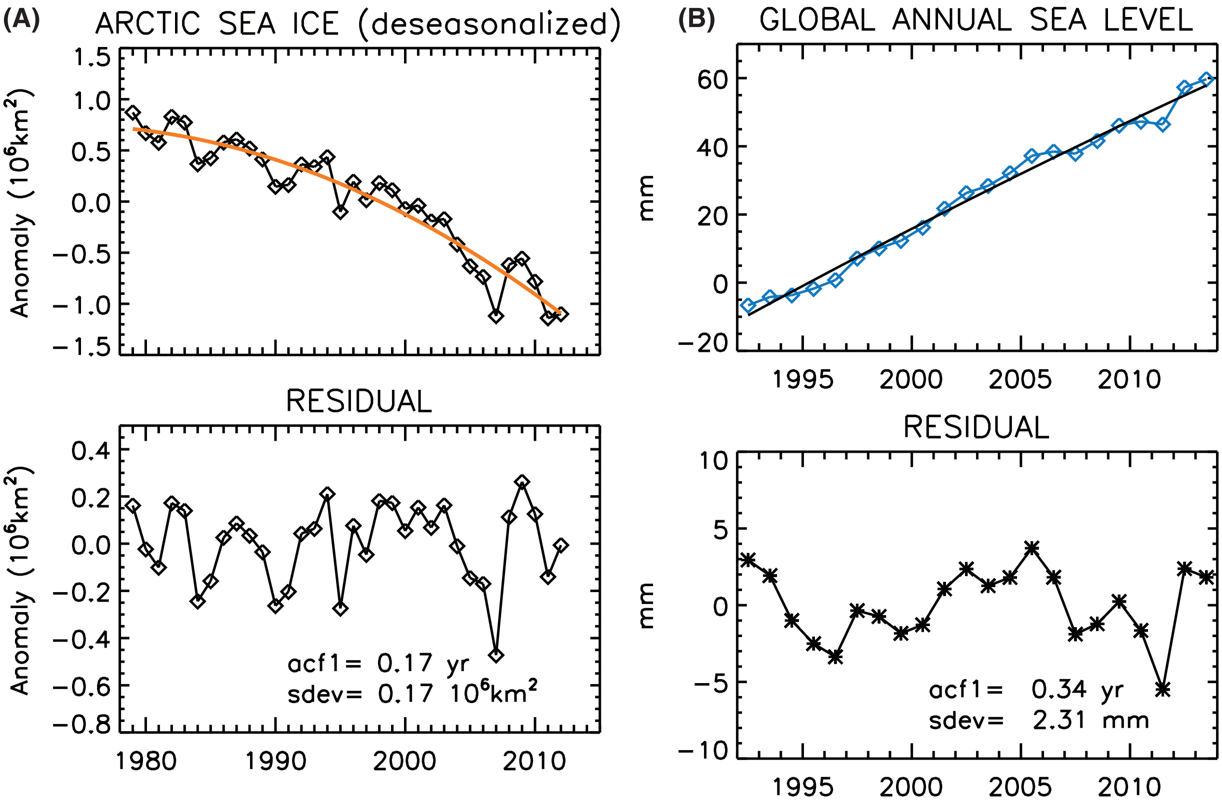

FIGURE B.4 (A) Arctic sea ice area and (B) global sea level. Shown in the upper panels are annual mean values of deseasonalized Arctic Sea Ice area (*left*) and global sea level (*right*). The smooth curves indicate long-term trends (estimated by polynomials), from which the residuals of the annual mean values are shown in the lower panels, as indicators of natural variability in these two climate change records. SOURCE: Courtesy of Judith L. Lean, Naval Research Laboratory.

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C

Full Framework Example: Narrowing Uncertainty in Climate Sensitivity

Quantified Objective: Reduce the Intergovernmental Panel on Climate Change Fifth Assessment (IPCC AR5) uncertainty in equilibrium climate sensitivity by a factor of 2.

IMPORTANCE

Uncertainty in climate sensitivity remains one of the largest sources of uncertainty in predicting the future economic impacts of climate change for any given emissions scenario (U.S. Interagency Working Group on Social Cost of Carbon, 2010, hereafter SCC, 2010). At 90 percent confidence, equilibrium climate sensitivity (ECS) has an uncertainty of roughly a factor of 4, which leads to uncertainty in economic impacts of a factor of roughly 16 (SCC, 2010) due the roughly quadratic relationship between warming and economic impacts. ECS is the long term equilibrium change of global average surface air temperature for a doubling of carbon dioxide. ECS is in essence the "volume dial" on the climate system. Yet, its uncertainty has remained unchanged since the early Charney report in 1979 (NRC, 1979). Because all forms of climate change will scale in magnitude with climate sensitivity, this is a critical quantified objective, with the highest rating level for the importance metric (*I*).

UTILITY

There are three primary independent approaches to estimate Earth's climate sensitivity. The first is to determine anthropogenic radiative forcing, and then compare that forcing to the amount of global temperature change. This method is limited primarily by our large uncertainty in the amount of anthropogenic aerosol radiative forcing, especially for aerosol indirect effects (see the discussion in Section 4.2.1 on the utility of measurements for aerosol forcing).[1]

The second method is to use the paleontological record of past changes in global temperature and carbon dioxide (the past 50 million years from ocean sediment records and over the last 800,000 years from ice cores; see

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[1] Although uncertainties also arise from the temperature record and the ocean heat storage record, they are much smaller than the uncertainty in anthropogenic aerosol forcing. The latter leads to a factor of 3 uncertainty in total anthropogenic forcing (Myhre et al., 2013), while the former are closer to 30 percent. Therefore, the aerosol uncertainty dominates the estimation of climate sensitivity from the recent observation record.

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Collins et al., 2013, Box 12.2, "Equilibrium Climate Sensitivity and Transient Climate Response," and references therein). This method gives as large an uncertainty as the first (Myhre et al., 2013).

The third method is to use observations to determine the individual major feedback mechanisms in the climate system. This method is based on the ability to separate feedback mechanisms in all climate models and to reconstruct the total climate system sensitivity from these components (Soden et al., 2008). It is also the only method that is capable of breaking the system into key components and verifying that climate models achieve the correct climate sensitivity for the right physical reasons. In this sense, it represents a method closest to a bottom-up physical explanation and verification of climate sensitivity. The primary feedback mechanisms are temperature (Planck[2]), snow/ice albedo, water vapor, temperature lapse rate, and cloud feedback. Of these, the most uncertain is cloud feedback, primarily resulting from uncertainty in low cloud feedback (Bony et al., 2006; Soden and Held, 2006; Soden et al., 2008; IPCC, 2007; Collins et al., 2013). Water vapor and temperature lapse rate have a strong negative correlation and their uncertainty is minimized when treated as a combined feedback.

Uncertainty in cloud feedback is currently estimated to be a factor of 3 to 4 larger than the other components (Myhre et al., 2013). Achieving the quantified objective of narrowing climate sensitivity with high confidence (i.e., understanding climate sensitivity and its components) will depend critically on obtaining observations able to constrain the uncertainty in cloud feedback, especially that due to low clouds as they are the dominant uncertainty in cloud feedback.

The primary effect of low clouds is to reduce the absorption of solar radiation by increasing Earth's albedo. Given their low altitude, they have very little compensating greenhouse effect. The magnitude of this effect on absorbed solar radiation is called the shortwave cloud radiative forcing (SW CRF) (Cess et al., 1990). Changing the amount of low cloud or the optical thickness of low cloud in a warming climate can cause warming to be either amplified or reduced because of the changing amount of SW CRF. Low cloud feedback is primarily determined by the change of global average SW CRF with changing global temperature (Soden et al., 2008). Note that cloud feedbacks in the longwave (LW) part of the spectrum also exist and are significant in magnitude, but in much better agreement for climate models. To fully determine cloud feedbacks both LW and SW feedbacks must be constrained with observations. LW cloud feedbacks must be corrected for cloud masking effects of temperature and water vapor feedbacks in the atmospheric column (Soden et al., 2008). The focus is on SW cloud feedbacks here because they dominate the uncertainty in the quantified objective. *SW CRF is at the highest level of the utility metric (U) rating to achieve the quantified objective in climate sensitivity.*

QUALITY

Efforts have been made to estimate cloud feedback from global radiation budget satellite observations, which have been made since 1978 (Loeb et al., 2012). Unfortunately, the early satellite record lacked both the continuity (i.e., overlap) and the absolute accuracy required to observe the subtle changes in CRF expected for even large cloud feedbacks. These early radiation budget observations were less accurate by a factor of 2 or more than recent CERES observations. The length of the scanner observations required to observe clear- and all-sky conditions for SW CRF were 2 years for Nimbus 7, 5 years for ERBE, and has now reached 14 years for CERES. None of these scanner records were overlapped in time.

The more recent CERES satellite observations beginning in 2000 have improved the accuracy and overlap (Loeb et al., 2012), but the record is still short relative to the noise of natural variability (Dessler, 2010; Dessler and Loeb, 2013; Wielicki et al., 2013), and challenges remain in verifying the level of calibration stability in orbit (Loeb et al., 2012).

Figure C.1 shows the relationship between instrument absolute accuracy, climate record length, and uncertainty in low cloud feedback as measured by decadal trends in SW CRF (Figure 3b from Wielicki et al., 2013). The vertical green arrow at lower left shows the range of signal from climate models of varying climate sensitivity from the CMIP3 archive (Soden and Vecchi, 2011). The uncertainties shown in Figure C.1 include instrument calibration uncertainty as well as orbit sampling uncertainty (see Chapter 2 of this report for the definition of uncertainties).

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[2] "Planck" denotes a simple radiative response, i.e., σT^4, where σ is the Stefan Boltzmann constant and T is the temperature (K).

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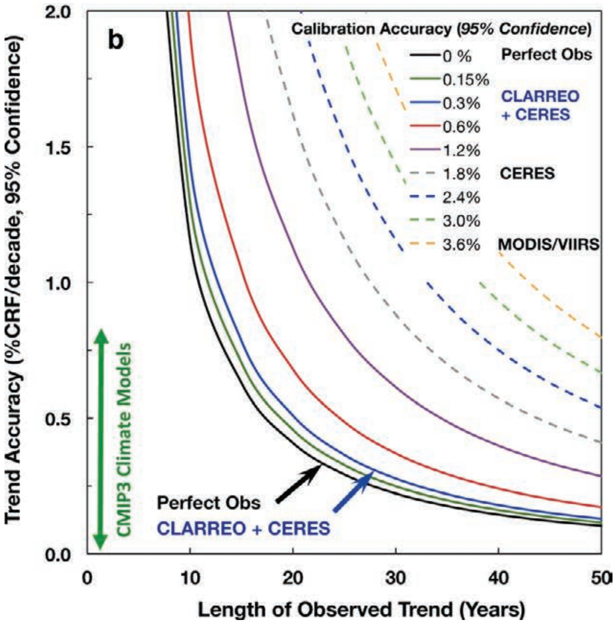

FIGURE C.1 Relationship between SW cloud feedback uncertainty measured as the trend of shortwave cloud radiative forcing (SW CRF), instrument accuracy, and data record length of the trend observed. Uncertainty from a perfect observing system is shown in the black line, the accuracy of current CERES (Clouds and Earth's Radiant Energy System) SW observation in grey, related MODIS (Moderate-Resolution Imaging Spectroradiometer) cloud property observations in yellow, and CERES if intercalibrated to future more accurate CLARREO (Climate Absolute Radiance and Refractivity Observatory) reference spectral observations. SOURCE: Courtesy of B.A. Wielicki, D.F. Young, M.G. Mlynczak, K.J. Thome, S. Leroy, J. Corliss, et al. 2013. Achieving climate change absolute accuracy in orbit. *Bulletin of the American Meteorological Society* 94:1519-1539. © American Meteorological Society. Used with permission.

The figure shows that calibration uncertainty dominates cloud feedback uncertainty and therefore will dominate the quality metric for this example. Consistent with Leroy et al. (2008) and Wielicki et al. (2013), the analysis in Figure C.1 includes the impact of drifts in calibration accuracy and/or gaps in the SW CRF record. Either change in calibration will lead to increases in trend uncertainty and increases in time to detect trends in SW CRF.

Narrowing uncertainty in climate sensitivity a factor of 2 will require reducing the uncertainty in SW CRF trends a factor of 2 below the range shown for CMIP3 in Figure C.1. The record length required to achieve this uncertainty level varies from 75 years for MODIS accuracy, to 50 years for CERES accuracy, to 23 years with CLARREO used as an orbiting reference calibration for CERES, and 19 years for a Perfect observing system. The economic impact of advancing knowledge of climate sensitivity by 20 years has been estimated to be on the order of $12 trillion U.S. dollars for the global economy (Cooke et al., 2014). To first order, this study found that the economic value was directly proportional to the number of years that information could be advanced.

Continuity for SW CRF can be defined at three different quality levels. The *first* level is without any broadband radiation observations for which we use MODIS/VIIRS as a typical example. This case shows a quality metric in time for the required trend accuracy of 75 years for MODIS, where 20 years for a "perfect" observing system = 55 years of time delay in quality. The *second* level of continuity is to continue the CERES data record, but without the CLARREO level of accuracy. This case gives a quality metric of 50 – 20 = 30 years of time delay. The *third* level of continuity is to fly CLARREO as an in orbit calibration reference for CERES, which provides a quality metric of 23 – 20 = 3 years of time delay. The committee concludes that there is a very large difference in the time to detect cloud feedbacks as a function of the type of observing system continuity employed.

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Since CLARREO can also be used to improve the accuracy of MODIS or VIIRS narrowband imager observations, could CLARREO calibration of VIIRS, VIIRS retrieved cloud and surface properties, and radiative transfer theory be combined to provide the accuracy needed in SW CRF for cloud feedback observations? A study of this type has been done using the CERES SYN data product comparing global climate anomalies of CERES observed fluxes with those determined from radiative transfer theory using MODIS-retrieved cloud properties and the resulting algorithm uncertainties are so large that they show little relationship between global SW CRF anomalies using the two methods. The committee concludes that the combination of CLARREO + VIIRS + theory does not appear to be a viable method for continuity of SW CRF at the quality metric (Q) levels required.

There is a link between this quantified objective for climate sensitivity and the quantified objective for radiative forcing (*Detect decadal change in the effective climate radiative forcing (ERF) to better than 0.05 W* m^{-2} *(1σ)).* The radiative forcing objective requires reduced uncertainty in the magnitude of indirect aerosol radiative forcing. Efforts to achieve such a reduction were a key motivator for the 2007 decadal survey committee's recommendation to develop the ACE (Aerosol-Cloud-Ecosystem) mission. For the climate sensitivity objective, decadal changes in aerosol indirect effect would affect decadal changes in SW CRF. If global aerosol emissions remain constant over the next several decades, the unknown aerosol indirect effect would not be a critical issue for SW CRF, since it would remain constant. For changing aerosol emissions, however, solving the climate sensitivity objective will require reducing uncertainty in aerosol indirect effect for the radiative forcing objective.

Finally, there is a link between CERES continuity and MODIS/VIIRS continuity. The CERES radiative flux products rely on MODIS/VIIRS surface and cloud property retrievals to determine the appropriate empirical anisotropy model to convert observed broadband radiance to broadband flux (Loeb et al., 2003).

SUCCESS PROBABILITY

All three of the continuity options considered in the quality section are considered: MODIS/VIIRS only, MODIS/VIIRS + CERES, and CLARREO + MODIS/VIIRS + CERES.

MODIS/VIIRS

MODIS has been providing continuous observations on the Terra spacecraft for 15 years and on the Aqua spacecraft for 13 years. The spacecraft and instruments are in good health and operation through 2020 looks very likely, but a formal probability of survival has not been determined. VIIRS launched on the Suomi-NPP spacecraft in 2011, and a follow-on JPSS (Joint Polar Satellite System) instruments are planned for launch in 2017 and 2022. The VIIRS instruments are part of the routine weather observing system and have a design lifetime of 7 years with 85 percent reliability. This predicts a reliability of these instruments at 14-year lifetime of 70 percent. In addition, similar quality imaging instruments will be added on the European Sentinel series of satellites. Given the long lifetime design and the existence of multiple satellite instrument time series, and the long term success with the global satellite weather observations, the success probability of the MODIS/VIIRS quality of imager observations is 90 percent or greater.

CERES + MODIS/VIIRS

CERES has been providing continuous observations on the Terra spacecraft for 15 years, and on the Aqua spacecraft for 13 years. Instrument design life is 5 years (85% reliability). There are two fully operational CERES instruments on Terra (i.e. fully redundant capability) and one fully operational CERES instrument on Aqua. Follow-on CERES instruments have launched on Suomi-NPP in 2011 and are planned for JPSS launches in 2017 and 2022. The lifetime design of the 2017 instrument is 5 years, and the lifetime design of the 2022 instrument is 7 years.

A quantitative gap risk analysis for the CERES instruments was carried out including instrument and spacecraft reliability and launch schedules (Loeb et al., 2009). Gaps were shown to very seriously degrade the accuracy of the climate record and the ability to observe cloud feedbacks. Tests were performed to verify if MODIS + radiative transfer theory could be used to cover the gaps in CERES observations, but this method proved inadequate to maintain climate record accuracy across data gaps or to reliably connect the CERES records across the gap.

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The committee concludes that gaps in the CERES record remain a critical limit on the ability to observe cloud feedback in the climate system. Given the long heritage of the CERES instruments and algorithms in orbit, success probability is limited primarily by planned launch schedule, instrument design life, and the ability to verify on orbit the stability of calibration over time. Current planned instrument builds on JPSS do not increase the accuracy over current CERES instruments. A reanalysis of the results in the Loeb et al. (2009) gap risk paper is needed to determine the success probability of overlapping CERES quality observations over the lifetime of JPSS-1 and JPSS-2.

CLARREO + CERES + MODIS/VIIRS

CLARREO provides much higher accuracy observations across the full reflected solar and infrared spectra than CERES or VIIRS, with an improvement of a factor of 3 to 5 in the infrared and a factor of 5 to 10 in the reflected solar. The advance in calibration would enable the CERES observations to survive gaps in the record (Wielicki et al. 2013). The results shown for CLARREO/CERES in Figure C.1 include using CLARREO to calibrate CERES quality radiation budget observations across future gaps in the climate record. CLARREO provides the same capability to MODIS or VIIRS as well as other low earth orbit or geostationary imagers and sounder instruments observing in the reflected solar or infrared spectrum (Wielicki et al., 2013; Lukashin et al., 2013).

In this form of continuity, CLARREO provides the accuracy and traceability to international physical standards (SI standards)[3] to meet the climate record accuracy as well as the ability to match angle/space/time with sufficient sampling to reduce calibration uncertainties in CERES and MODIS/VIIRS. Further, in this form of continuity, gap impact is low, so that low gap risks are not required. This can save resources by lengthening the time between satellite launches from the current typical 5 years (e.g., 85% reliability) to 10 years (70% reliability). Success probability for surviving gaps in this form of continuity is 100 percent. The primary risk for this approach is the need to launch new reflected solar and infrared spectrometer instruments and to prove in orbit the calibration verification levels that have been demonstrated by CLARREO-like instruments in the laboratory. Using past NASA research missions and their ability to achieve planned accuracy levels, the likelihood of success is estimated at 80 percent or greater.

FINAL SCORING

Final continuity scoring for three forms of SW CRF continuity for the climate sensitivity quantified objective[4] is given in Table C.1 using the benefit (*B*) formula from Chapter 3 of $B = I \times U \times Q \times S$, where *I* ranges from 1 to 5, *U* ranges from 0 to 1.0, *Q* ranges from 0 to 1.0, and *S* ranges from 0 to 1.0 (see Section 4.4 for scoring rationale). The Q_1 metric from Section 4.3.2 is used to score quality for this example. This metric is also used in

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[3] See "SI Traceability," on the NASA website, "CLARREO: Achieving climate change absolute accuracy in orbit," at http://clarreo.larc.nasa.gov/about-SITrace.html.

[4] This example treats the continuity of Top of Atmosphere SW CRF, which cannot be observed from the ground. The committee did consider, however, whether ground measurements might be relevant for verifying calibration shifts across gaps in the satellite record. While surface based observations of transmitted solar radiation are correlated with top of atmosphere reflected fluxes, the relationship is very noisy (~ 70 W m^{-2} 1 σ instantaneous noise as shown by time/space matched CERES and BSRN (Baseline Surface Radiation Network) observations, or roughly 30 percent of the insolation at the CERES overpass time), so that matching observations to within 0.3 W m^{-2} as required for the SW CRF accuracy (0.3% of 100 W m^{-2} global mean SW CRF at 95% confidence) would require $(30 \times 2/0.3)^2$—40,000—matched surface/CERES observations to show consistency at 0.3 percent of CRF (95% confidence). Requiring this once per year to monitor change, with 365 CERES orbit overflights of each surface site, would require 40,000/365 = 100 surface sites (versus the current 30 BSRN sites).

In addition, such a comparison would add the major uncertainty of using radiative transfer models to relate TOA reflected SW flux to surface transmitted SW flux. Such models are considered to have accuracies of ~ 5 percent, not 0.3 percent. Finally, the accuracy of the highest quality BSRN surface SW flux measurements is about 5 W m^{-2} or about 2 percent of the CERES orbit crossing average surface insolation. This is about 7 times less accurate than the 0.3 percent required for monitoring SW CRF. From sampling, radiative transfer theory, and calibration accuracy perspectives, the bridging of a gap in SW CRF using surface observations is currently impossible, and the committee is not aware of any future capabilities in any of the three uncertainties (all would need to be solved) that would allow such a capability in the near future. As a result of these considerations, the committee has not included such a gap bridge in the analysis shown here. This does not, however, invalidate the relevance of such an approach for other observations such as air temperature (GRUAN [GCOS Reference Upper Air Network] or GPS-RO [Global Positioning System-Radio Occultation]), ice sheet elevation (IceBridge), CO_2 or ozone monitoring networks. The usefulness of surface or aircraft observations as gap fillers will vary widely with quantified objective.

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TABLE C.1 Final Continuity Scoring for Quantified Objective Climate Sensitivity

Three Forms of Shortwave Cloud Radiative Forcing	Importance (*I*)	Utility (*U*)	Quality (*Q*)	Success Probability (*S*)	Benefit (*B*)
MODIS/VIIRS	5	1	0.0	1.0	0
CERES/MODIS/VIIRS	5	1	0.23	0.9	1.0
CLARREO/CERES/MODIS/VIIRS	5	1	0.83	0.8	3.3

NOTE: CERES, Clouds and Earth's Radiant Energy System; CLARREO, Climate Absolute Radiance and Refractivity Observatory; MODIS, Moderate-Resolution Imaging Spectroradiometer; VIIRS, Visible Infrared Imaging Radiometer Suite.

Appendix B. We calculate the quality metric based on the CLARREO Pathfinder mission in the President's 2016 budget beginning observations in 2020. We assume instrument lifetimes of 10 years (consistent with the examples in Appendix B), a value more typical of MODIS/VIIRS/CERES lifetimes than the 5 years used in the analysis for Figure C.1. Given the 2020 start year for the CLARREO observation, we give MODIS/VIIRS/CERES credit for 20 years of on orbit operations since 2000. This acts to increase their quality metric value by reducing their time delay versus a perfect observing system starting in 2020. The CLARREO/CERES/MODIS/VIIRS record begins in 2020 and has no adjustment for existing climate record.

Table C.1 shows the large impact of quality on the benefit provided for the quantified objective for climate sensitivity, with a factor of 3.3 increase over the current observing system. This is true despite the 20 year head start of the CERES/MODIS/VIIRS record. In the future, it would be useful to extend the equations in Section 4.3.2 to not only include past record lengths, but to also separate the trend effects of absolute calibration uncertainty and data gap issues from the effects of overlapped climate records with uncertain slow calibration drifts over time. Each causes errors in climate trend observations but in different ways. In orbit calibration drifts caused by material degradation or contamination will tend to be systematic in sign and to cause systematic biases in climate trends. For example, CERES stability estimate in orbit is 0.5 percent at 95 percent confidence (Loeb et al., 2012) but placing this level of consistent SW CRF trend in Figure C.1 would lead to a systematic bias in cloud feedback with a magnitude that would limit improvement in cloud feedback uncertainty to 40 percent no matter how long the climate record.

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D

Full Framework Example: Determining Sea Level Rise and Its Acceleration

Quantified Objective: Determine sea level rise to ±1 mm yr^{-1} $decade^{-1}$ globally.

IMPORTANCE

Sea level rise is the result of two major components of climate change: the warming of the ocean, which is the major repository of the heat stored in the Earth system, and the water added to the ocean from land surface changes, such as increased river runoff and the melting of the polar ice sheets and mountain glaciers. Changes in sea level measurements provide a critical constraint on estimates of ocean heat storage (see Appendix E) and land water storage, as well as ice loss. Storage of heat in the ocean buffers the rise in atmospheric temperatures by absorbing heat from the atmosphere.

The melting of land ice from climate change could potentially raise sea level by more than 1 m by the end of the 21st century, jeopardizing lives and properties in the world's coastal zones and islands. A one-meter rise by the end of the century is estimated to have global economic impacts of trillions of U.S. dollars (Sugiyama et al., 2008) and displacement of 10 percent of the world's population if no adaptation is applied.

The rate of sea level rise is increasing. Between 1970 and 2010, sea level rose at an average rate of 2.0 mm yr^{-1} while the rate estimated for the period of 1993-2010 increased to 3.2 mm yr^{-1} (Church et al., 2013). From these estimates, the acceleration of sea level rate is about 1 mm yr^{-1} $decade^{-1}$ and a determination of the acceleration of sea level at this level with a high degree of confidence is needed to make timely detection of future change and to validate model projections.

UTILITY

Before the advent of satellite observations of sea surface height with radar altimetry, it was not possible to make direct determination of the global mean sea level. The sparsely located tide gauges were not able to sample the uneven spatial distribution of sea level change, leading to biased measurement. The 20-year record (Figure D.1, from Nerem et al., 2010) from satellite altimetry is the first directly measured time series of the global mean sea level. The satellite's uniform global sampling also reveals the complex geographic pattern of sea level change over the past 20 years (Figure D.2, from Willis et al., 2010), underscoring the uncertainty from sparse tide gauge measurement. Satellite altimetry provides a unique utility for addressing the quantified objective for sea level.

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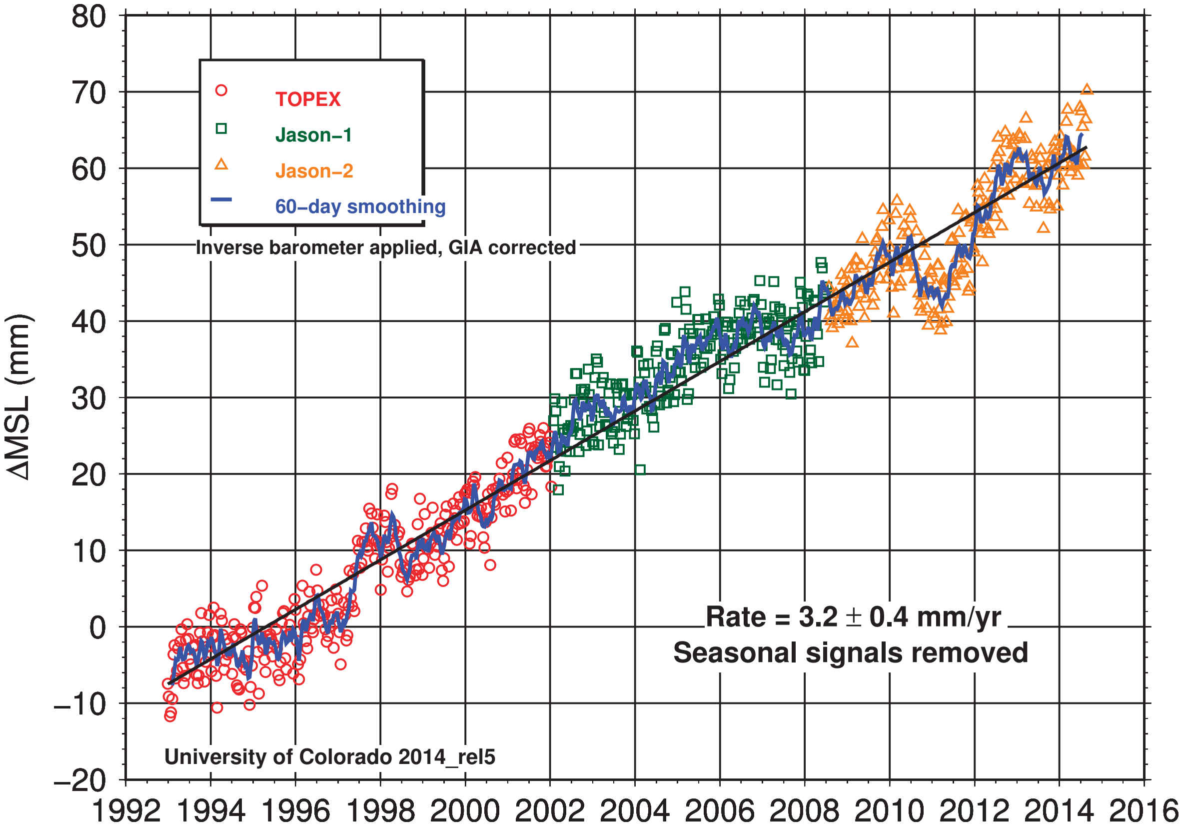

FIGURE D.1 Global mean sea level record from a series of satellite altimetry missions. SOURCE: R.S. Nerem, D. Chambers, C. Choe, and G.T. Mitchum, Estimating mean sea level change from the TOPEX and Jason altimeter missions, *Marine Geodesy* 33(1 Supp 1):435, 2010.

The contributions to recent sea level rise have roughly equal partitions among the steric effect from ocean warming, the melting of mountain glaciers, and the melting of polar ice sheets (Gardner et al., 2013; Shepherd et al., 2012). The measurement of the change of Earth's gravity field from space gravimetry demonstrated by the GRACE Mission (Tapley et al., 2004) has for the first time provided direct observation of the mass added to the ocean from ice melt. The difference between altimetry and gravity measurements (Figure D.3, from Llovel et al., 2014) is attributed to the steric sea level change, which has been observed by an in-situ network of float measurements (Argo). The intercomparison of satellite and in situ observations has provided cross-calibration and mutual validation of the measurement system. Figure D.3 illustrates that the observations from altimetry, GRACE, and Argo are consistent with each other to the extent of the observational errors.

The ability to diagnose sea level change in terms of its steric and mass components represents a key step toward understanding the physical processes. GRACE provides a unique utility to understand the process of global sea level change while Argo provides an essential in-situ component for calibrating and validating the spaceborne observations.

QUALITY

Satellite altimetry missions with the accuracy and precision of the TOPEX (Ocean Topography Experiment)/Poseidon and the Jason series are capable of reaching 0.4 mm/yr accuracy in global mean sea level (Nerem et al.,

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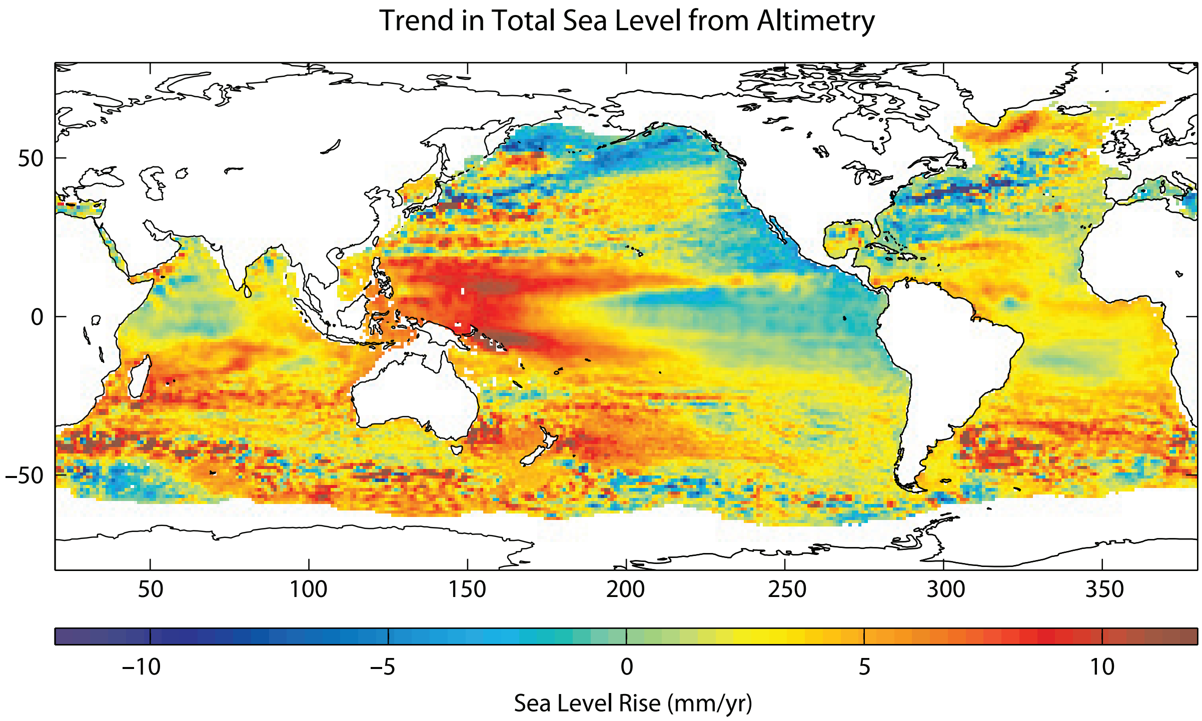

FIGURE D.2 The trend of sea level change from 1992-2008 estimated from satellite altimetry missions. SOURCE: J.K. Willis, D.P. Chambers, C.-Y. Kuo, and C.K. Shum, Global sea level rise: Recent progress and challenges for the decade to come, *Oceanography* 23(4):26-35, 2010.

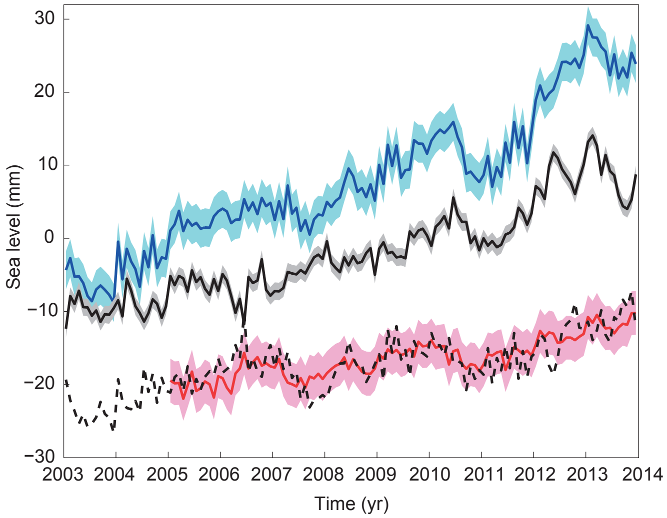

FIGURE D.3 Global mean sea level variations. The estimates are observed variations by satellite altimetry (blue), ocean mass contributions based on GRACE (Gravity Recovery and Climate Experiment) data (solid black), and steric sea level based on in situ observations (red). The dash black curve shows the indirect steric mean sea level estimate inferred by removing ocean mass contributions from the observed sea level time series. Seasonal signals have been removed from all curves. Curves are offset for clarity. Shading where shown denotes 1*s* uncertainty of respective estimates. SOURCE: Reprinted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, W. Llovel, J.K. Willis, F.W. Landerer, and I. Fukumori, Deep-ocean contribution to sea level and energy budget not detectable over the past decade, *Nature Climate Change* 4:1031-1035, copyright 2014.

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TABLE D.1 Final Continuity Scoring for the Quantified Objective Sea Level Rise

	Importance (I)	Utility (U)	Quality (Q)	Success Probability (S)	Benefit (B)
Satellite radar altimetry	5	1	0.99	1.0	5.0
Satellite gravity	5	1	0.99	1.0	5.0

2010). The uncertainty in the measurement is dominated by the knowledge of land motion in the error budget of tide gauge calibration of altimetry. The time scale of the land motion is much longer than a decade. The uncertainty in determining the change in sea level rate over a decade is then reduced to the formal error in the estimate of a linear trend, which is about 0.07 mm/yr.

From the equation for the accuracy factor of the quality metric in Section 4.3.1, the quality (accuracy factor) of the altimetry observation of the sea level variable for meeting the quantified objective has a score of 0.99.

The estimation of the contribution of ice melt to the gravity variation determined by GRACE is significantly affected by the uncertainty in the knowledge of the Glacial Isostatic Adjustment (GIA). However, the time scale of the GIA is also much longer than a decade. The error associated with the GIA is thus cancelled in the estimation of the decadal change of the mass component of sea level change, leading to an uncertainty of 0.1 mm per year on decadal scale.

From Section 4.3.1, the quality (accuracy) of the GRACE observation of the mass component of sea level has a score of 0.99.

SUCCESS PROBABILITY

Satellite altimetry missions since TOPEX/Poseidon have had lifetimes of more than twice their designed life of 5 years; the technology as well as implementation is considered mature. The probability of success is rated in thus in the highest category with a score of 1.0 (see Section 4.4 for scoring rationale).

The GRACE mission, although first of its kind, has lasted more than twice its designed life of 5 years. Again, as explained in Section 4.4, the probability of success is assessed to be 1.0.

FINAL SCORING

Final continuity scoring for the quantified objective is given in Table D.1 using the benefit (B) formula from Chapter 3 of $B = I \times U \times Q \times S$, where I ranges from 1 to 5, U ranges from 0 to 1.0, Q ranges from 0 to 1.0, and S ranges from 0 to 1.0 (see Section 4.4 for scoring rationale).

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E

Full Framework Example: Determining the Change in Ocean Heat Storage

Quantified Objective: Determining the change in ocean heat storage within 0.1 W m^{-2} per decade.

IMPORTANCE

Over 90 percent of the heat from anthropogenic warming has been stored in the ocean as reported in the recent IPCC report (Rhein et al., 2013). Observation of the ocean heat storage is key to understanding the heat budget of the planet and prediction of future climate. The uptake of heat by the ocean is estimated to be 0.5-1 W m^{-2} (Loeb et al., 2012; Trenberth and Fasullo, 2010 Trenberth et al., 2014). Detection of its change by 10-20 percent per decade is essential.

UTILITY

An observing system consisting of satellite altimetry (Jason-series), spaceborne gravimetry (Gravity Recovery and Climate Experiment [GRACE] series), and in-situ network of floats (Argo) has demonstrated the capability of determining the ocean heat storage from the measurement of sea level, ocean mass, and the upper ocean heat content. It should be noted however that the Argo coverage is limited to the upper 2,000 m of the ocean with poor coverage of the tropical Asian Archipelago which might be important to the analysis of the global mean sea level variability. The ocean heat is estimated from the total steric change calculated as the altimetry sea level-GRACE determined mass component. The comparison of the space determined steric sea level to Argo estimated value for the upper 2000 m is consistent within measurement errors of both systems. This is validation of the space system over decadal scale of the overlap between altimetry and GRACE.

Recent studies (Wunsch and Heimbach, 2014; Llovel et al., 2014; Purkey and Johnson, 2010) have suggested that the deep ocean heat change over the past two decades is roughly 10 percent of that of the upper ocean. The ocean heat storage estimated from the difference between altimetry and ocean mass measurement is consistent with the in situ measurement within the observational uncertainties. The three measurements provide a somewhat redundant and self-calibrating observing system.

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TABLE E.1 Final Continuity Scoring for the Quantified Objective Ocean Heat Storage

	Importance (I)	Utility (U)	Quality (Q)	Success Probability (S)	Benefit (B)
Radar altimetry + gravity	5	1	0.68	1.0	3.4

QUALITY

The 1-σ uncertainty of Argo measurement of the upper 2,000 m on decadal scale is 0.1 W m^{-2} (von Schuckmann and Le Traon, 2011). Assuming the calibration errors of altimetry (from the tide gauge calibration) and GRACE (from the glacial isostatic adjustment correction) have time scales much longer than a decade, the 1-σ error in the full-depth steric sea level rate, computed from the difference between altimetry and GRACE observations over a decade (in which the calibration errors cancel out), is about 0.1 mm yr^{-1}, roughly equivalent to 0.1 W m^{-2}.

The sea level uncertainty of 0.1 mm yr^{-1} is estimated from the combination (root-sum-squares) of the altimetry error of 0.07 mm yr^{-1} and the GRACE mass component of sea level error of 0.1 mm yr^{-1} (Llovel et al., 2014).

The above analysis indicates that the current observing system has a capability of determining the rate of change in ocean heat storage with a 1-σ uncertainty of 0.1 W m^{-2} over decadal scales. From the equation for the accuracy factor of the quality metric in Section 4.3.1, the quality (accuracy factor) of the observation of ocean heat storage change for meeting the quantified objective has a score of 0.68.

Without in situ calibration, however, the performance of the space part of the observing system of altimetry and gravity might not be stable over multi-decadal scales. There has not been sufficient observation to characterize the possible long-term stability. The analysis is thus quite liberal in the sense that the long-term stability is not accounted for as well as the conversion of the uncertainty of sea level of 0.1 mm yr^{-1} to 0.1 W m^{-2} of ocean heat storage. The latter depends on the vertical distribution of the heat, which was simply assumed to be uniform in the calculation.

PROBABILITY OF SUCCESS

Satellite altimetry missions since TOPEX (Ocean Topography Experiment)/Poseidon have had lifetimes for more than twice their designed life of 5 years; the technology as well as implementation has become mature. The probability of success is rated in its highest category with a score of 1.0 (see Section 4.4 for scoring rationale).

The GRACE mission, although first of its kind, has lasted more than twice its designed life of 5 years. The probability of success is assessed to have a score of 1.0. The score for the probability of success for estimating ocean heat storage change is also estimated to be 1.0, which is the multiplication of that of altimetry (1.0) and gravimetry (1.0).

FINAL SCORING

Final continuity scoring for the quantified objective is given in Table E.1 using the benefit (B) formula from Chapter 3 of $B = I \times U \times Q \times S$, where I ranges from 1 to 5, U ranges from 0 to 1.0, Q ranges from 0 to 1.0, and S ranges from 0 to 1.0 (see Section 4.4 for scoring rationale).

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F

Full Framework Example: Determining Ice Sheet Mass Balance

Quantified Objective: Determining changes in ice sheet mass balance within 15 Gt yr^{-1} *per decade or 1.5 Gt* yr^{-2}.

Ice sheets are losing mass at an accelerating rate of 300 Gt yr^{-1} per decade, or 30 Gt yr^{-2}. Detecting changes at the 5 percent level is essential for understanding the interactions of ice sheets and climate at the regional level and for improving projections from numerical models. Details of ice flow dynamics must be resolved at the glacier scale.

IMPORTANCE

The melting of glaciers and ice sheets into the ocean is a dominant part of the total contribution to sea level rise (Vaughan et al., 2013) and by far the largest uncertainty in projecting sea level rise in the coming centuries (Church et al., 2013).

The contribution of ice sheets to sea level was 0.3±0.1 mm yr^{-1} in 1997-2001 and increasing to 1.2 ± 0.3 mm yr^{-1} in 2007-2011 (1 mm = 360 Gt). For small glaciers and ice caps, the contribution was 0.76 mm yr^{-1} in 1993-2009 and 0.83 mm yr^{-1} in 2005-2009 (Vaughan et al., 2013). Projections of sea level rise by 2100 range from 0.21 to 0.83 m, however with low confidence in the ability of ice sheet numerical models to project rapid dynamical changes in Antarctica and Greenland, which results in a systematic underestimation of ice sheet contributions (Church et al., 2013).

Detecting the rate of change in ice mass balance per decade is essential, along with the observation of rapid changes and the detection of dynamic instabilities. In 1997-2011, ice sheet loss accelerated at 300 Gt yr^{-1} per decade or 0.9 mm yr^{-1} per decade (Vaughan et al., 2013).

UTILITY

A glacier and ice sheet observing system has demonstrated its capability and value to provide modern, consistent, comprehensive estimates of ice sheet mass balance over the last decades, observe rapid glacier changes in Greenland and West Antarctica, and detect instabilities in ice dynamics. This system consists of satellite altimetry (Ice, Cloud, and land Elevation Satellite [ICESat] series), airborne altimetry and radar sounding (Operation

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IceBridge—OIB), satellite radar interferometry (international synthetic aperture radar (SARs) with NASA participation), satellite time-variable gravity (Gravity Recovery and Climate Experiment [GRACE] series), and in situ automated weather stations (AWS). Employing this multiple-instrument approach provides complementary and essential information about net changes in mass and the underlying physical components that drive these changes such as surface mass balance processes and ice dynamics. Taken together, the geophysical variables measured by this observing system are sufficient to achieve the quantified objective.

Gravity measurements provide the most accurate synoptic-scale information about net mass change, and help evaluate surface mass balance fields at the large scale. Ice sheet velocity measurements provide detailed information about ice flow dynamics, the largest uncertainty in sea level rise. Ice volume measurements complement gravity and velocity measurements. Given the complementarity of the three geophysical variables for achieving the quantified objective, each variable is given the same utility score in this example.

QUALITY

Satellite radar interferometry shall measure ice motion with a precision of 100 mm at 100 m spatial scale, balanced pole to pole, with a near daily frequency re-visit to observe rapid change in ice dynamics and measure long term trends and spatial patterns in ice mass change. This enables measurements of ice sheet discharge into the ocean with a precision of 3 percent, combined with estimates of surface mass balance from regional atmospheric climate models at the 7 percent level, which in turns helps detect changes in ice mass loss with a precision of 1 Gt yr^{-2} in Greenland and 2 Gt yr^{-2} in Antarctica (Rignot et al., 2011).

Satellite laser altimetry shall measure ice sheet surface elevation to detect ice-sheet elevation change rates to accuracies better than 1 cm yr^{-1} on an annual basis and 25 cm yr^{-1} on fast moving glaciers at spatial scales of 10 km. This will enable detection of changes of 80 Gt yr^{1} in Antarctica and 25 Gt yr^{-1} in Greenland if the density at which volume changes are taking place is well known. Detection of acceleration in mass loss not well documented for laser altimetry (Shepherd et al., 2012). Available data showing non-linear, dynamically-controlled glacier response (Csatho et al, 2014) suggest a high degree of gap intolerance in maintaining the required quality of continuity measurements,

Satellite time-variable gravity shall measure change in Earth's geoid with a precision better than 1 mm to degree 55 (363 km). This will enable measurements of acceleration in mass loss of 1 Gt yr^{-2} in Greenland and 4 Gt yr^{-2} in Antarctica (Velicogna et al., 2014).

Based on the above assessment of measurement precisions and accuracies and using the subjective quality rating scale given in Table 4.5, the committee attaches quality ratings of 0.9 to expected space-borne gravity and ice velocity measurements and 0.6 for laser altimetry from a combination of satellite and airborne platforms.

PROBABILITY OF SUCCESS

ICESat-1 had a lifetime of 7 years or twice its designed lifetime of 3 years, yet did not operate in continuous mode. ICESat-2 will employ a new photon counting technology for its sole instrument, the Advanced Topographic Laser Altimeter System (ATLAS). ATLAS represents a new approach to spaceborne determination of surface elevation in order to improve elevation estimates in sloped areas, as well as rough land surfaces such as crevasses. Specifically, ATLAS is a micropulse, multibeam, photon-counting laser altimeter with lower energy, a shorter pulse width, and a higher repetition rate relative to the instrument that was onboard ICESat. The probability of success is 0.8 (see Section 4.4 for scoring rationale).

Operation Ice Bridge has been operating in a precursor mode since 1993 as a suborbital program at NASA.[1] The technology and implementation is mature to the level of a mission series. The probability of success is rated the highest with a score of 1.0.

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[1] The Arctic Ice Mapping group (Project AIM) at the NASA Goddard Space Flight Center Wallops Flight Facility has been conducting systematic topographic surveys of the Greenland Ice Sheet since 1993, using scanning airborne laser altimeters (NASA ATM) combined with Global Positioning System (GPS) technology. Operation IceBridge campaigns began in 2009; see http://icebridge.gsfc.nasa.gov/.

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TABLE F.1 Final Continuity Scoring for the Quantified Objective Ice Sheet Mass Balance

	Importance (I)	Utility (U)	Quality (Q)	Success Probability (S)	Benefit (B)
ICESat-2 + OIB (laser altimetry series)	5	1	0.6	0.8	2.4
GRACE FO (gravity series)	5	1	0.9	1.0	4.5
NISAR[a] (ice velocity series)	5	1	0.9	0.8	3.6

a Interferometric synthetic aperture radar (InSAR) is a technique that uses two or more synthetic aperture radar (SAR) images over the same region to derive surface topography or surface motion. NISAR refers to the NASA-ISRO (Indian Space Research Organization) [Interferometric] Synthetic Aperture Radar (see http://nisar.jpl.nasa.gov).

Satellite imaging radars have flown since 1991, without the purpose to provide interferometry data over ice sheets, but providing hands-on experience with ice sheet observations. NASA flew Seasat in 1978 and several shuttle-borne radar missions in the 1990s, with plans to return with a dedicated interferometric SAR free flyer mission in 2020. The technology and implementation both benefit from decades of experience with SAR. The probability of success is 0.8.

The GRACE mission was designed to last 5 years and has lasted more than 12 years. The probability of success of GRACE follow-on mission using a combination of existing and new technology is high and has a score of 1.

FINAL SCORING

NASA is extending the gravity, ice volume, and ice velocity measurements by operating OIB and developing GRACE Follow-on, ICESat-2, and NISAR (NASA-ISRO synthetic aperture radar). Relative to this example quantified Earth science objective, previous experience indicates that laser altimetry, through a combination of satellite and airborne capabilities, will obtain a high-quality measurement that partially meets the quantified objective, whereas the quality of the gravity and ice velocity measurements will largely meet the quantified objective. Accordingly, the final continuity scoring for the quantified objective is given in Table F.1 using the benefit (B) formula from Chapter 3 of $B = I \times U \times Q \times S$, where I ranges from 1 to 5, U ranges from 0 to 1.0, Q ranges from 0 to 1.0, and S ranges from 0 to 1.0 (see Section 4.4 for scoring rationale).

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G

Full Framework Example: Global Land Carbon Sinks

Quantified Objective: Determine the global land carbon sink and quantify this globally to ±1.0 Pg C year^{-1} aggregating from the 1° × 1° scale.

IMPORTANCE

Carbon cycles through the atmosphere as gases, such as carbon dioxide (CO_2) and as carbon in plants and soils, in ocean water, in phytoplankton, and in marine sediments. CO_2 is released to the atmosphere from combustion of fossil fuels, by land cover changes on Earth's surface, by biomass burning, by respiration of green plants, and by decomposition of carbon in dead vegetation and in soils, including carbon in permafrost. The atmospheric concentrations of CO_2 control atmospheric temperatures, through their absorption of outgoing long wave radiation and thus indirectly control sea level, via regulation of planetary ice volumes and ocean temperatures. A depiction of the carbon cycle showing reservoirs, fluxes or transfers between reservoirs, and the processes responsible is shown in Figure G.1.

Using the atmospheric O_2/N_2 ratio and the change in atmospheric δ^{13} C, an average global land carbon sink of 2.9 ±0.8 Pg C per year has been determined (Le Quéré et al., 2014). This determination is a global number with no spatial specificity of any kind. Because the land removes a quarter of the carbon emitted to the atmosphere, we need to determine the locations of and mechanisms for this large terrestrial carbon sequestration (Figure 4.1). To achieve this quantified objective, satellite observations of CO_2 fluxes at monthly time-scales and spatial scales of ~1° × 1° over multiple annual cycles are critical, in addition to several other satellite observing systems. These satellite observations must be linked to process models at the 1° × 1° scale. For major urban areas, and for estimation of anthropogenic emissions, flux determinations need to be at spatial scales on the order of 10 km.

At the same time, soil respiration and decomposition must be addressed with linked of in situ process studies and satellite data sources to determine how this important land carbon cycle component can be addressed. Should the land carbon sink cease or diminish, atmospheric CO_2 concentrations would increase more rapidly.

The current system of atmospheric CO_2 measurements do not adequately constrain land process-based carbon cycle models to allow diagnosis and/or attribution of the land and ocean carbon sinks and sources/fluxes with any confidence—hence, the models yield widely varying patterns of carbon land and ocean sources and sinks. Testing and improving the surface and ocean parameterizations in Earth system models that calculate the surface-

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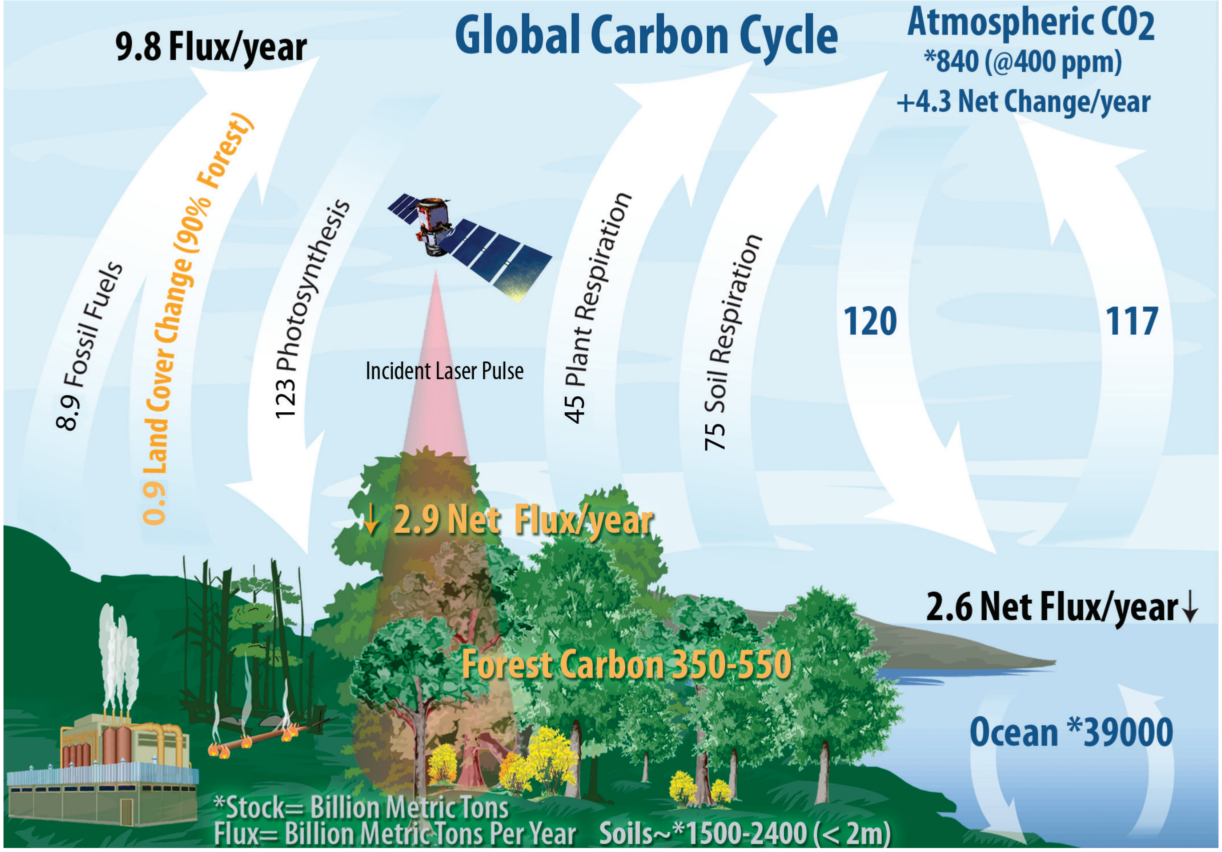

FIGURE G.1 Depiction of the carbon cycle showing reservoirs, fluxes or transfers between reservoirs, and the processes responsible. The atmospheric CO_2 concentration is a principal determinant of Earth's temperature and thus climate. Units are billion metric tons for carbon stocks and billion metric tons/year for fluxes. One ppm atmospheric CO_2 is the equivalent of 2.13 Pg carbon. SOURCE: Updated from Ciais et al. (2013), with respiration data from Schlesinger and Bernhardt (2013), ocean fluxes from Westberry and Behrenfeld (2013), and land photosynthesis from Beer et al. (2010). Image courtesy of NASA Goddard Space Flight Center.

atmosphere fluxes of energy, water, and carbon, is essential for developing a capability to predict future climate, but this has proved to be a difficult and challenging task.

In addition to the required satellite observations, in situ observations are also needed to confirm satellite-measured CO_2 concentrations and determine soil and vegetation carbon quantities. Understanding the carbon cycle thus requires a "full court press" of satellite and in situ observations because all of these observations must be made at the same time. The importance factor for the carbon cycle is thus assessed to be 5 as it is a fundamental component of climate and directly influences the CO_2 content of the atmosphere.

UTILITY

Before the satellite era, it was impossible to quantitatively study the global regional carbon cycle. Only limited in situ measurements, such as Dave Keeling's Mauna Loa atmospheric CO_2 concentration with time, were available before the satellite era. With satellites, we are now able to quantify ocean and land photosynthesis (Westberry and Behrenfeld, 2013; Beer et al., 2010), measure the air-sea CO_2 exchange (Gruber et al., 2009), measure atmospheric

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CO_2 concentrations (Chevallier et al., 2007), determine more accurately forest and woodland biomass (Houghton, 2005), accurately map forest disturbance and regrowth (Hansen et al. 2010), and accurately map biomass burning and determine resulting carbon emissions (van der Werf et al., 2010).

Required satellite observations to achieve accurate measurement of forest and woodland carbon involve: (1) determining the volume of carbon contained in forests and woodlands globally, a three-dimensional determination, translates into two-dimensional 30 m mapping with Landsat or equivalent, and the height or third dimension from lidar and radar; (2) disturbance mapping using Landsat or equivalent and radar at 30 m, to map deforestation and regrowth; (3) detection and quantification of biomass burning using instruments like MODIS (Moderate-Resolution Imaging Spectroradiometer) or VIIRS (Visible Infrared Imaging Radiometer Suite) that detect the thermal emissions of fires within the forest and woodland strata coupled with the biomass of the areas burned; (4) quantifying net primary production of forests and woodlands to determine the carbon uptake or release of forests; and (5) passive and active monitoring of CO_2 concentrations to confirm if forest and woodland are sources or sinks of atmospheric CO_2. A feature of the carbon cycle, like other quantified science objectives such as mesoscale convective system evolution, precipitation and the hydrological cycle, and surface fluxes of heat is the requirement for simultaneous observations from several satellite observing systems.

The utility rating for achieving the carbon cycle objectives of CO_2 concentrations, land photosynthesis, land biomass and change, biomass burning, and respiration and decomposition is estimated to be 1.0 because of the impressive existing, new, and planned satellite systems that address carbon cycle processes directly.

QUALITY

To achieve the accuracy and precision required for quantifying the global land carbon sink ±1.0 Pg C per year by aggregation from 1° × 1° land surface data requires use of satellite data from GOSAT, OCO-2 (Orbiting Carbon Observatory-2), SMAP (Soil Moisture Active-Passive), Landsat, and MODIS/VIIRS. These satellite observing systems must be coupled to numerical land process models at the 1° × 1° scale over multiple annual cycles. The quality of quantifying the atmospheric CO_2 concentration, land photosynthesis, and biomass burning is determined to be 0.95 because these components for this quantified science objective will have improved respective accuracies when surface weighted X_{CO2} (column-averaged CO_2 concentrations) estimates are retrieved from high-resolution GOSAT and OCO-2 spectroscopic observations. The quality for land biomass and change and respiration and decomposition are both estimated to be 0.8 because of the large uncertainties in these carbon cycle components (Table 4.4). Gaps in all of these carbon cycle observations can be tolerated for periods of <1 year while continuity over spans of tens of years is needed.

SUCCESS PROBABILITY

Landsat and MODIS satellites have all operated for much longer time spans than their design lives, including 27 years for Landsat-5 and 15 years for MODIS on the Terra platform. Landsat-8, MODIS/VIIRS, GOSAT (Greenhouse gases Observing Satellite), OCO-2, and SMAP are currently operating successfully and the GEDI (Global Ecosystem Dynamics Investigation) laser altimeter mission is scheduled for launch in 2020. The probability of success for atmospheric CO_2 concentration retrievals is estimated to be 0.95 because OCO-2 is operating successfully. The probability of success for land photosynthesis is estimated to be 0.9 because, while MODIS and VIIRS are operating successfully, SMAP data are needed to improve land photosynthesis and this work is just beginning. The probability of success for land biomass, disturbance, and recovery is estimated to be 0.8 because our current estimates of total above-ground plant carbon has an uncertainty of ±100 Pg C. The probability of success for biomass burning is estimated to be 0.95 based on the successful use of Landsat and MODIS/VIIRS to estimate carbon emissions from biomass burning. The probability of success for determining soil respiration and decomposition is estimated to be 0.8 because this is the largest land surface flux uncertainty (Table 4.4). While SMAP data are just beginning, the linkage of SMAP data with in situ soil respiration and decomposition process models needs to be accelerated for greater carbon cycle understanding.

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TABLE G.1 Final Continuity Scoring for the Quantified Objective Global Land Carbon Sinks

	Importance (I)	Utility (U)	Quality (Q)	Success Probability (S)	Benefit (B)
CO_2 concentrations	5	1	0.95	0.95	4.5
Land photosynthesis	5	1	0.95	0.90	4.3
Land biomass and change	5	1	0.80	0.8	3.2
Biomass burning	5	1	0.95	0.95	4.5
Respiration and decomposition	5	1	0.8	0.80	3.2

FINAL SCORING

Final continuity scoring for the quantified objective is given in Table G.1 using the benefit (B) formula from Chapter 3 of $B = I \times U \times Q \times S$, where I ranges from 1 to 5, U ranges from 0 to 1.0, Q ranges from 0 to 1.0, and S ranges from 0 to 1.0 (see Section 4.4 for scoring rationale).

Of the five components needed to achieve the quantified objective for land carbon sink, atmospheric CO_2 measurements and biomass burning score the highest benefit score because they have the lowest measurement uncertainties. Land biomass and respiration/decomposition have the highest uncertainties and have the lowest benefit rating. Land photosynthesis falls between these carbon cycle components. All five of these components are needed to achieve the objective of identifying the land carbon sink while quantifying this globally to ±1.0 Pg C per year aggregating from the 1° × 1° scale.

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H

Committee and Staff Biographical Information

BYRON D. TAPLEY, *Chair,* is the Clare Cockrell Williams Centennial Chair in Engineering and is director of the Center for Space Research at the University of Texas, Austin. His research interests include orbit mechanics, precision orbit determination, nonlinear parameter estimation, satellite data analysis, and the uses of methods from these areas to study the Earth and planetary system. Currently, he is the mission principal investigator for the Gravity Research and Climate Experiment (GRACE) Mission, which is the first NASA Earth System Pathfinder Mission. A recent focus of his research has been directed to applying the GRACE measurements to determine accurate models for Earth's gravity field and using these measurements for studies of climate driven mass exchange between Earth's dynamic system components. Dr. Tapley was also the chair of the NASA Advisory Council's Earth Science Subcommittee. He is a member of the National Academy of Engineering (NAE) and a fellow member of American Institute of Aeronautics and Astronautics (AIAA), the American Geophysical Union (AGU), and the American Association for the Advancement of Science. The NASA Medal for Exceptional Scientific Achievement, the NASA Public Service Medal, the AAS Brouwer Award, the AIAA Mechanics and Control of Flight Award and the AGU Charles A. Whitten Medal are among the awards he has received. He has been a principal investigator for seven NASA and international missions. He is a registered professional engineer in the State of Texas. He earned his Ph.D. in engineering mechanics, his M.S. in engineering mechanics, and his B.S. in mechanical engineering from the University of Texas, Austin. His previous National Research Council (NRC) membership service includes the Panel on Climate Variability and Change, the Space Studies Board (SSB), the Panel to Review NASA's Earth Observing System in the Context of the USGCRP, the Committee on NASA's Space Station Engineering and Technology Development, and the Aeronautics and Space Engineering Board (ASEB), the Geophysics Research Forum, and the steering committee for the Study and Workshop on NASA's Space Research and Technology Program.

MICHAEL D. KING, *Vice Chair,* is senior research scientist in the Laboratory for Atmospheric and Space Physics at the University of Colorado, Boulder. Dr. King is also the science team leader for the MODIS instrument that flies on the Aqua and Terra satellites currently in orbit. He served as senior project scientist of NASA's Earth Observing System (EOS). He joined NASA Goddard Space Flight Center (GSFC) as a physical scientist and previously served as project scientist of the Earth Radiation Budget Experiment (ERBE). His research experience includes conceiving, developing, and operating multispectral scanning radiometers from a number of aircraft platforms in field experiments ranging from arctic stratus clouds to smoke from the Kuwait oil fires and biomass burning in Brazil and southern Africa. Dr. King is also interested in surface reflectance properties of natural surfaces as well as

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aerosol optical and microphysical properties. Earlier, he developed the Cloud Absorption Radiometer for studying the absorption properties of optically thick clouds as well as the bidirectional reflectance properties of many natural surfaces. He was formerly the principal investigator of the MODIS Airborne Simulator, an imaging spectrometer that flies onboard the NASA ER-2 aircraft—an instrument that has aided in the development of atmospheric and land remote sensing algorithms for MODIS, which is used for studies of Earth's environment from space. Dr. King is a member of the NAE, a fellow of the AGU, the American Meteorological Society (AMS), and the Institute of Electrical and Electronic Engineers (IEEE), a recipient of the Verner E. Suomi Award of the AMS for fundamental contributions to remote sensing and radiative transfer, and a recipient of the Space Systems Award of the AIAA for NASA's Earth Observing System. He received his M.S. and Ph.D. in atmospheric sciences from the University of Arizona. Dr. King is currently a member of the NRC's Committee on Earth Science and Applications from Space, and previously served on the Board on Atmospheric Sciences and Climate, and the Climate Research Committee.

MARK R. ABBOTT began serving as president and director of the Woods Hole Oceanographic Institution on October 1, 2015. Until this time, Dr. Abbott was at Oregon State University (OSU), beginning in 1988, where he served as dean of the College of Earth, Ocean and Atmospheric Sciences since 2001. Before OSU, he served as a member of the technical staff at the Jet Propulsion Laboratory (JPL) and as a research oceanographer at Scripps Institution of Oceanography. Dr. Abbott's research focuses on the interaction of biological and physical processes in the upper ocean and relies on both remote sensing and field observations. He is a pioneer in the use of satellite ocean color data to study coupled physical/biological processes. As part of a NASA Earth Observing System interdisciplinary science team, Dr. Abbott led an effort to link remotely sensed data of the Southern Ocean with coupled ocean circulation/ecosystem models. His field research included the first deployment of an array of bio-optical moorings in the Southern Ocean as part of the U.S. Joint Global Ocean Flux Study (JGOFS). Dr. Abbott has been a member of the National Science Board since 2006. He also currently chairs the U.S. JGOFS Science Steering Committee and is the vice chair of the Oregon Global Warming Commission. He is currently a member of the board of trustees for the Consortium for Ocean Leadership and the board of trustees for the University Corporation for Atmospheric Research. His past advisory posts include chairing the Coastal Ocean Applications and Science Team for NOAA and chairing the U.S. Joint Global Flux Study Science Steering Committee. He has also been a member of the Director's Advisory Council for JPL and NASA's MODIS and SeaWiFS science teams and the Earth Observing System Investigators Working Group. He was recently named the 2011 recipient of the Jim Gray eScience Award, presented by Microsoft Research. He received his B.S. in conservation of natural resources from the University of California, Berkeley, and his Ph.D. in ecology from the University of California, Davis. Dr. Abbott is a national associate member of the National Academies and is currently a member of the NRC's Space Studies Board, chair of the Committee on Earth Science and Applications from Space, and a member of the Panel on the Review of the Draft 2013 National Climate Assessment (NCA) Report. Amongst his prolific NRC service, Dr. Abbott served on the NRC's Committee on Evaluating NASA's Strategic Direction, the Committee on the Assessment of NASA's Earth Science Programs, the Committee on the Role and Scope of Mission-Enabling Activities in NASA's Space and Earth Science Missions, and the Panel on Land-Use Change, Ecosystem Dynamics and Biodiversity for the 2007 Earth science and applications from space decadal survey.

STEVEN A. ACKERMAN is a professor of atmospheric and ocean sciences and director of the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin, Madison. Dr. Ackerman's research focuses on satellite remote sensing and has produced several new methodologies for interpreting satellite observations, which has led to improved understanding of the radiative properties of clouds, a critical factor in weather and climate. Dr. Ackerman is principal investigator for the following NASA projects: Refinement and Maintenance of the Moderate Resolution Imaging Spectroradiometer (MODIS) Cloud Mask Algorithm on Terra and Aqua; Comparison of A-Train Cloud Retrievals and Multi-Instrument Algorithm Studies; and Algorithm Maintenance and Validation of MODIS Cloud Mask, Cloud Top-Pressure, Cloud Phase and Atmospheric Sounding Algorithms. He is co-principal investigator for NASA's Global Analysis of MODIS Level-3 Cloud Properties and Their Sensitivity to Aggregation Strategies and Land Surface Characterization Using High Spectral Resolution AIRS and Moderate Spatial Resolution MODIS Observations from the EOS Aqua Platform. He was recently elected a fellow of the

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Wisconsin Academy of Science, Arts and Letters and is the recipient of numerous awards, including the NASA Exceptional Public Service Medal and the American Meteorological Society's (AMS's) Teaching Excellence Award. He received his M.S. in atmospheric science from Colorado State University and his Ph.D. in atmospheric science from Colorado State University. Dr. Ackerman is currently a member of the NRC's Committee on Earth Science and Applications from Space.

JOHN J. BATES is principal scientist of Remote Sensing at the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS) National Climatic Data Center (NCDC). Prior to becoming principal scientist, he was chief of the Remote Sensing Applications Division at NCDC. Dr. Bates's primary research interests include satellite observations of the global water and energy cycle, air-sea interactions, and climate variability. He currently serves on the board of directors of the AGU in addition to being a member of the organization. Prior to working at NCDC, Dr. Bates was a Mellon Foundation post-doctoral fellow at the Scripps Institution of Oceanography; meteorologist at the NOAA Boulder Climate Diagnostics Center and then the NOAA Boulder Environmental Technology Laboratory. He is the recipient of numerous awards, including the 1998 Editors' Citation for Excellence in Refereeing for *Geophysical Research Letters*, the 2004 NOAA Administrator's Award, and the Outstanding Heroic Act Award in 2009 for Excellence in Public Service from Buncombe Country, North Carolina. Dr. Bates received his B.S. in meteorology from Florida State University and his M.S. and Ph.D. in meteorology from the University of Wisconsin, Madison. He previously served on the NRC's Panel on the Global Energy and Water Cycle Experiment (GEWEX) and the Workshop on Uncertainty Management in Remote Sensing of Climate Data.

RAFAEL L. BRAS is the provost and executive vice president for academic affairs at the Georgia Institute of Technology. He is also a professor in the School of Civil and Environmental Engineering and School of Earth and Atmospheric Sciences. He currently holds the K. Harrison Brown Family Chair. His research interests are hydrology, hydroclimatology, and hydrometeorology. From 2008-2010, Dr. Bras was a distinguished professor and dean of the Henry Samueli School of Engineering of the University of California, Irvine. For 32 years prior to joining UCI he was a professor at Massachusetts Institute of Technology (MIT). He is past chair of the MIT faculty, former head of the Civil and Environmental Engineering Department and director of the Ralph M. Parsons Laboratory at MIT. Dr. Bras has served as advisor to many government and private institutions. Some of the most significant include: advisory board, Engineering Directorate, NSF; NRCs Board of Atmospheric Sciences and Climate; chairman, Earth Systems Sciences and Applications Committee of NASA and the NASA Advisory Committee; advisor to departments at Cornell University, Princeton University, Johns Hopkins, Technion, RPI, University of Puerto Rico, the University of California, Irvine, Instituto Veneto; the Stockholm Water Foundation and Prize; and Clarke Prize. Dr. Bras is on the board of directors of the AGU and also a member of the board of trustees of the University Corporation for Atmospheric Research and of the Foundation for Puerto Rico. Dr. Bras has received many honors and awards, including: honorary degree for the University of Perugia, Italy; Hispanic Engineer Hall of Fame member; NASA Public Service Medal; the Macelwane Medal of AGU; and the John Simon Guggenheim Fellowship. In addition to being a member of the NAE, he is also a member of the Academy of Arts and Sciences of Puerto Rico, and the Mexican National Academy of Engineering and Mexican National Academy of Sciences. He is an elected fellow of AGU and served as past president of the Hydrology section of the AGU, and is also a fellow of the American Society of Civil Engineers, the AMS, and the American Association for the Advancement of Science. He received his B.S. and M.S. in civil engineering from MIT and his Sc.D. in water resources and hydrology from MIT. He most recently served on the NRC's Committee on New Orleans Regional Hurricane Protection Projects, and was also a member of the Board on Atmospheric Sciences and Climate, among other NRC service.

ROBERT E. DICKINSON is professor in the Department of Geological Sciences at the University of Texas at Austin. He is a respected leader in dynamic meteorology, physical climatology, and climate modeling for the last 4 decades. He first delineated the way planetary scale-Rossby waves interact with the mean flow—a process central to understanding the general circulation of the atmosphere. He has also established the major role of foliage

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in climate dynamics and made major contributions to other problems. His areas of interest include the dynamics of atmospheric planetary waves, stratospheric dynamics, models of global structure and dynamics of terrestrial and planetary thermosphere, NLTE infrared radiative transfer in planetary mesopheres, global climate modeling and processes, the role of land processes in climate systems, the modeling role of vegetation in regional evapotranspiration, and the role of tropical forests in climate systems. His recent research has focused on climate variability and change, aerosols, the hydrological cycle and droughts, land surface processes, the terrestrial carbon cycle, and the application of remote sensing data to modeling of land surface processes. He is an elected member of both the U.S. National Academy of Sciences and the National Academy of Engineering, an honorary member of the European Geophysical Society and the European Geo-sciences Union and a foreign member of Chinese Academy of Sciences. He has been a member of numerous scientific advisory organizations, including the NRC. He holds M.S. and Ph.D. degrees in meteorology from MIT. He currently serves on the *Proceedings of the National Academy of Sciences* editorial board, as well as the NRC's Committee to Advise the U.S. Global Change Research Program and Panel on the Review of the Draft 2013 National Climate Assessment (NCA) Report. He has also served on numerous climate and environmental science-related committees for the NRC in the past.

RANDALL R. FRIEDL is manager of the Earth System Science Formulation Office within JPL's Earth Science and Technology Directorate. In that role he is responsible for fostering research and mission concepts in response to competitive opportunities. Prior to his current assignment, Dr. Friedl held positions as the deputy director for research in the Engineering and Science Directorate and as chief scientist in the Earth Science and Technology Directorate. Dr. Friedl's research interests are focused on gas and particle reactions relevant to Earth's stratosphere and troposphere. He has participated in a number of international and national assessments, notably, as lead author for the IPCC Special Report on Aviation and the Global Atmosphere (1999), as contributing author for the IPCC Third Assessment Report on Climate Change (2001). In addition to his JPL activities, Dr. Friedl has served several roles at NASA Headquarters. From 1994 to 1996 he was the project scientist for the Atmospheric Effects of Aviation Project. During that tenure, he developed and organized numerous research efforts, including several aircraft field campaigns to study aircraft impacts on the upper troposphere. For his work on the aviation-related issues he received a NASA Exceptional Service Medal in 1997 and a NASA Group Achievement Award in 1999. Dr. Friedl spent a year and a half at NASA Headquarters as the deputy chief scientist for Earth science within the Science Mission Directorate (SMD) and as the deputy for science within the Earth Science Division of SMD. In those roles, Dr. Friedl was the primary advisor on Earth science issues to the NASA associate administrator and earth science director and was tasked with formulating internal strategy for the NASA Earth science program as well as joint strategies with other federal agencies. He also served on the NRC's Panel on Earth Science Applications and Societal Needs for the 2007 Earth science and applications from space decadal survey.

LEE-LEUNG FU is a JPL fellow and senior research scientist at JPL, California Institute of Technology. He has been the project scientist for JPL's satellite altimetry missions since 1988, including TOPEX/Poseidon, Jason, and Ocean Surface Topography Mission/Jason-2. He is currently the project scientist for the U.S./France joint Surface Water and Ocean Topography Mission (SWOT), which is being developed as the next generation altimetry mission for measuring water elevation on Earth. Dr. Fu's research has been focused on the dynamics of ocean waves and currents ranging from small-scale internal gravity waves to ocean basin-scale circulation. He received a B.S. degree in physics from National Taiwan University and a Ph.D. in oceanography from MIT and Woods Hole Oceanographic Institution. He is a member of the NAE and a fellow of the AGU and the AMS. Recently he was awarded the COSPAR International Cooperation Medal for his leadership in the development and continuation of satellite altimetry missions.

CHELLE L. GENTEMANN is a senior principal scientist at Remote Sensing Systems, a research-oriented business located in Santa Rosa, California. Dr. Gentemann's research focuses on air-sea interactions; upper ocean physical processes; microwave remote sensing of geophysical variables, including sea surface temperature and sea ice; and multi-instrument data fusion. She has served on many national and international science teams and working groups, including the NASA Sea Surface Temperature Science Team, the NASA Satellite Ocean Atlas team, the

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Japan Aerospace Exploration Agency (JAXA) GCOM-W AMSR2 Science Team, the International Group for High Resolution SST Science Team and Advisory Council, and the MIT Educational Council. She is currently chair of the NASA PO.DAAC User Working Group. Dr. Gentemann was principal investigator of the Multi-instrument Improved Sea Surface Temperature (MISST) Project that received the National Oceanographic Partnership Program Excellence in Partnering Award. She was part of the Satellite Ocean Atlas Team that was awarded the NASA Group Achievement Award for outstanding achievement in utilization of multiple observations from space for the study of the global oceans. She currently has 28 peer-reviewed papers published and is a member of the AGU, AMS, and IEEE Geoscience and Remote Sensing Society. Dr. Gentemann received her B.S. in earth, atmospheric, and planetary sciences from MIT, her M.S. in physical oceanography from Scripps Institute of Oceanography, and her Ph.D. in meteorology and physical oceanography from the University of Miami. Dr. Gentemann is currently a member of the NRC's Committee on Earth Science and Applications from Space.

KATHRYN A. KELLY is professor in the School of Oceanography at the University of Washington (UW) and principal oceanographer at the Applied Physics Laboratory. Prior to joining the UW faculty, she was a scientist at the Woods Hole Oceanographic Institution for over a decade. Her research focuses on air-sea interaction and the ocean's transport of various properties. Recently, Dr. Kelly has been studying ocean heat transport in the Atlantic Ocean to understand its impact on oceanic heat fluxes to the atmosphere. Her primary scientific interest is the role of the ocean in climate, which she studies using large data sets, particularly from satellite instruments, in collaboration with numerical modelers and scientists who make in situ measurements. She is a fellow of the AMS and also served as co-chair for the implementation plan for the Atlantic Meridional Overturning Circulation multi-agency initiative. Dr. Kelly received her B.S. in engineering mathematics and statistics from the University of California, Berkeley, and her Ph.D. in physical oceanography from the Scripps Institution of Oceanography for research into the causes of SST anomalies in the California current using satellite infrared data. She is a member of NASA's Ocean Surface Topography and Sea Surface Temperature science teams and was a member of NASA's Ocean Vector Winds Science Team for 2 decades. She previously served on the NASA Earth System Science and Applications Advisory Committee and on the steering committee of the NRC's 2007 Earth science and applications from space decadal survey.

JUDITH L. LEAN is senior scientist for Sun-Earth System Research in the Space Science Division of the Naval Research Laboratory. After completing her Ph.D. she worked for CIRES at the University of Colorado, Boulder, and then joined the U.S. Naval Research Laboratory. She is the recipient of a number of NASA research grants, in collaboration with other SSD and U.S. scientists, and is currently a co-investigator on the SORCE, TIMED/SEE, SDO/EVE and GLORY/TIM space missions. The focus of her research is to understand the Sun's variability using measurements and models, and to determine the impact of this variability on the Earth system, including climate change, the ozone layer, and space weather. She has published 116 papers in journals and books, and delivered over 250 presentations documenting her research. A member of the AGU, IAGA, AAS/SPD, and AMS, Dr. Lean was elected a fellow of the AGU in 2002, a member of U.S. National Academy of Sciences in 2003, and a member of the American Philosophical Society in 2013. She has served on a variety of NASA, NSF, NOAA, and NRC advisory committees. She has a Ph.D. in atmospheric physics from the University of Adelaide, Australia. Dr. Lean most recently completed service as a member of the NRC's 2012 solar and space physics decadal survey. She also chaired the NRC's Working Group on Solar Influences on Global Change, and was a member of the Committee on a Strategy to Mitigate the Impact of Instrument De-scopes and De-manifests on the NPOESS and GOES-R Spacecraft, and the Panel on Climate Variability and Change of the 2007 Earth science and applications from space decadal survey, among other committees.

JOYCE E. PENNER is the Ralph J. Cicerone Distinguished University Professor of Atmospheric Science and associate chair of the Department of Atmospheric, Oceanic and Space Sciences at the University of Michigan. Dr. Penner's research focuses on improving climate models through the addition of interactive chemistry and the description of aerosols and their direct and indirect effects on the radiation balance in climate models. She is also interested in urban, regional, and global tropospheric chemistry and budgets, cloud and aerosol interactions and

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cloud microphysics, climate and climate change, and model development and interpretation. Dr. Penner has been a member of numerous advisory committees related to atmospheric chemistry, global change, and Earth science, including the United Nations Intergovernmental Panel on Climate Change (IPCC) and, consequently, a co-winner of the 2007 Nobel Peace Prize. She was the coordinating lead author for IPCC (2001) Chapter 5 on aerosols. She is a member of COSPAR committee formulating an Earth science roadmap. Dr. Penner received a B.A. in applied mathematics from the University of California, Santa Barbara, and her M.S. and Ph.D. in applied mathematics from Harvard University. She is currently a member of the NRC Committee on Assessment of NASA's Earth Science Program and the U.S. National Committee for the International Union of Geodesy and Geophysics and the vice chair of the NRC's Committee on Earth Science and Applications from Space. She previously served as a member of the Space Studies Board, the planning committee for the Workshop on Uncertainty Management in Remote Sensing of Climate Data, and Panel on Climate Variability and Change for the 2007 decadal survey on Earth science and applications from space.

MICHAEL J. PRATHER is a professor of Earth System Science at the University of California, Irvine. His research focuses on the simulation of the physical, chemical, and biological processes that determine atmospheric composition; development of detailed numerical models of photochemistry and atmospheric radiation; and global chemical transport models that describe ozone and other trace gases. Post-Ph.D., Dr. Prather was a research fellow at Harvard University and then a scientist at the Goddard Institute for Space Studies, including also managing NASA Headquarters programs on upper atmosphere and aviation impacts. A fellow of the AGU and a member of the Norwegian Academy of Science and Letters, he served from 1997 through 2001 as editor-in-chief of *Geophysical Research Letters*. He received a B.A. in mathematics from Yale University, a B.A. in physics from the University of Oxford, and a Ph.D. in astronomy and astrophysics from Yale University. Prather currently participates in key United Nations' environmental efforts, including the international ozone assessments (1985, 1988, 1989, 1991, 1994, 2010, 2014) and climate assessments (IPCC: 1992, 1995, 1999, 2001, 2007, 2013, 2014). Dr. Prather has served on numerous NRC committees, most recently as a member of the Assessment of NASA's Earth Science Programs. He also previously served on the Committee on Methods for Estimating Greenhouse Gas Emissions, the Panel on Climate Variability and Change of the 2007 decadal survey on Earth science and applications from space, and the Committee for Review of the U.S. Climate Change Science Program Strategic Plan.

ERIC J. RIGNOT is Chancellor Professor of Earth System Science at the University of California, Irvine. He is also a senior research scientist and joint faculty appointee at the California Institute of Technology's JPL. Dr. Rignot's primary research interests lie in glaciology, climate change, radar remote sensing, ice sheet numerical modeling, radar interferometry, radio echo sounding, and ice-ocean interactions. His research group focuses on understanding the interactions of ice and climate, ice sheet mass balance, ice-ocean interactions in Greenland and Antarctica, and current/future contributions of ice sheets to sea level change. He has 22 years of experience in glaciology, he has been the advisor of 9 Ph.D. students, 7 postdocs, and has published more than 130 peer-reviewed papers (h-index 48) including 14 in *Science*, 2 in *Nature*. He received the following awards: NASA Exceptional Scientific Achievement Medal in 2003 and 2007, NASA Outstanding Leadership in 2012, Nobel Peace Prize attributed to IPCC AR4 authors in 2007, three JPL Director Award for Outstanding Research Publication, and 12 NASA Certificates of Recognition. Dr. Rignot is a fellow of the AGU and a member of the International Glaciological Society and AAAS, a lead author of IPCC AR5, and former editor of *Geophysical Research Letters*. He received his B.S. in engineering from Ecole Centrale Arts et Manufactures Paris, his M.S. in astronomy and astrophysics from University Paris VI, a double M.S. in aerospace engineering and electrical engineering from the University of Southern California (USC), and his Ph.D. in electrical engineering from USC.

WILLIAM L. SMITH is a distinguished professor of the Department of Atmospheric and Planetary Sciences at the Hampton University, Hampton, Virginia. He is also professor emeritus of the Department of Atmospheric and Oceanic Sciences at the University of Wisconsin, Madison. Professor Smith was the principal investigator of several satellite programs for NOAA; professor of atmospheric and oceanic sciences at the University of Wisconsin, Madison where he also directed the Cooperative Institute for Meteorological Satellite Studies (CIMSS) and

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subsequently the positions of chief, Atmospheric Sciences Division; and senior scientist at the NASA's Langley Research Center until 2004. Dr. Smith is an active satellite and airborne experimentalist. Most notably, Dr. Smith pioneered the hyper-spectral resolution sounding technique that is being used for current and future polar satellite advanced infrared sounding systems (e.g., the Aqua/AIRS, MetOp/IASI, and NPP/NPOESS CrIS). Dr. Smith has published more than 150 papers in the scientific literature and has contributed to books used for scientific research and teaching. He has also received numerous awards for his research accomplishments in the field of atmospheric science. Dr. Smith currently serves on the NRC's Committee on Evaluating NOAA's Plan to Mitigate the Loss of Total Solar Irradiance Measurements from Space, and prior to that served on the Telescopes/Observatories and Instruments and Instruments Panel of the Committee for the Review of NASA's Capability Roadmaps, and the Committee on NOAA NESDIS Transition from Research to Operations.

COMPTON J. TUCKER is a senior scientist at NASA GSFC. His research focus on Earth systems through the use of satellite remote sensing, including global vegetation dynamics, Landsat Forest Deforestation, and the Famine Early Warning System for Africa via USAID. He is also adjunct professor at the University of Maryland, Department of Geographical Sciences, where he teaches courses on remote sensing. Prior to working at NASA GSFC, Dr. Tucker worked at the Grassland Biome at Colorado State University, and was then a National Academy of Sciences postdoctoral fellow. He has received numerous awards, including two NASA Exceptional Scientific Achievement Medals, the Henry Shaw Medal of the Missouri Botanical Garden, the National Air and Space Museum Trophy for Current Achievement, and most recently the Galathea Medal of the Royal Danish Geographical Society, among others. Dr. Tucker received his B.S. degree in biology and his M.S. and Ph.D. degrees in forestry from Colorado State University.

BRUCE A. WIELICKI is senior scientist for radiation sciences in the Science Directorate at NASA Langley Research Center. He currently serves as Science Team lead for the CLARREO (Climate Absolute Radiance and Refractivity Observatory) decadal survey mission. He served as principal investigator on the CERES Investigation for 18 years, and as a co-investigator on the NASA Cloudsat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite. For more than 20 years, Dr. Wielicki's research has focused on clouds and their role in Earth's radiative energy balance. Specific research interests include the following: remote sensing of single and multiple cloud layer properties from multispectral imagery; validation of remotely-sensed cloud properties; effect of clouds on Earth's radiation budget; and cloud radiative transfer modeling. Dr. Wielicki received his B.S. degree in applied math and engineering physics from the University of Wisconsin, Madison, and his Ph.D. degree in physical oceanography from Scripps Institution of Oceanography. He received a NASA Exceptional Scientific Achievement Award in 1992 and the Henry G. Houghton Award from the AMS in 1995. He recently completed service on the NRC's Committee for Evaluating NOAA's Plan to Mitigate the Loss of Total Solar Irradiance Measurements from Space.

STAFF

ARTHUR A. CHARO, *Study Director,* has worked since 1995 as a senior program officer with the SSB. He is the staff officer for the Board's Committee on Earth Science and Applications from Space and the Committee on Solar and Space Physics, and has directed studies resulting in some 36 reports, notably the first NRC "decadal survey" in solar and space physics (2003) and Earth science and applications from space (2007). Recently, he served as the study director for the second NRC decadal survey in solar and space physics, a midterm assessment of the Earth science decadal survey, and an assessment of impediments to interagency collaboration on space and Earth science missions. Dr. Charo received his Ph.D. in experimental atomic and molecular physics in 1981 from Duke University and was a post-doctoral fellow in chemical physics at Harvard University from 1982-1985 where he worked on developing techniques to enable far-infrared laser spectroscopy of weakly bound complexes formed in a molecular beam. He then pursued his interests in national security and arms control as a Fellow at Harvard University's Center for Science and International Affairs. From 1988 to 1995, he worked as a senior analyst and study director in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment. In addition to contributing to NRC reports, he is the author of research papers in the field of molecular spectroscopy; reports on

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arms control and space policy; and the monograph, Continental Air Defense: A Neglected Dimension of Strategic Defense (University Press of America, 1990). Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and a Harvard-Sloan Foundation Fellowship (1987-1988). He was a 1988-1989 AAAS Congressional Science Fellow, sponsored by the American Institute of Physics.

LEWIS B. GROSWALD[1] is an associate program officer for the SSB. Mr. Groswald is a graduate of George Washington University, where he received a master's degree in international science and technology policy and a bachelor's degree in international affairs, with a double concentration in conflict and security and Europe and Eurasia. Following his work with the National Space Society during his senior year as an undergraduate, Mr. Groswald decided to pursue a career in space policy, with a focus on educating the public on space issues and formulating policy. He has worked on NRC reports covering a wide range of topics, including near-Earth objects, orbital debris, life and physical sciences in space, and planetary science.

ANESIA WILKS joined the SSB as a program assistant in August 2013. Ms. Wilks brings experience working in the National Academies conference management office as well as other administrative positions in the D.C. metropolitan area. She has a B.A. in psychology, magna cum laude, from Trinity University in Washington, D.C.

KATIE DAUD[2] is a research associate for the SSB and the ASEB. Previously, she worked at the Smithsonian National Air and Space Museum's Center for Earth and Planetary Studies as a planetary scientist. Ms. Daud was a triple major at Bloomsburg University, receiving a B.S. in planetary science and Earth science and a B.A. in political science.

MICHELLE THOMPSON[3] is a Lloyd V. Berkner Space Policy Intern. She is a Ph.D. student in planetary sciences at the University of Arizona's Lunar and Planetary Laboratory. Her research is focused on understanding the effects of space weathering on airless body surfaces. Ms. Thompson uses transmission electron microscopy to study microstructural and microchemical signatures of space weathering in lunar and asteroidal surface samples returned from the NASA Apollo missions and the JAXA Hayabusa mission. She has received several awards for her presentations at scientific conferences and was recently awarded a NASA Earth and Space Science Fellowship for her research. She serves on several committees as a student in Tucson, including as a representative for the graduate students to the faculty, coordinator for visiting colloquium speakers, and organizer of non-academic career seminars for the students in her department.

ANGELA DAPREMONT[4] is a Lloyd V. Berkner Space Policy Intern. She recently graduated from the College of Charleston with a B.S. in geology and a minor in French and francophone studies. Ms. Dapremont developed an interest in the merging of science and policy as a result of participating in meetings with congressional aides about science education and funding during her final year of undergraduate study. She has conducted research in the field of planetary geology at NASA Johnson Space Center and NASA GSFC. As an SSB autumn intern, she has had the opportunity to utilize her research skills and has accomplished her goal of gaining insight into the formulation and implementation of space policy. She hopes to continue to work in science policy and use her experiences as a guide for the next steps in her research career.

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[1] Through June 20, 2014.

[2] From September 22, 2014.

[3] From October 6, 2014, to December 12, 2014.

[4] From September 29, 2014, to March 27, 2015.

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MICHAEL H. MOLONEY is the director for Space and Aeronautics at the SSB and the ASEB of the National Academies of Sciences, Engineering, and Medicine. Since joining the ASEB/SSB, Dr. Moloney has overseen the production of more than 40 reports, including four decadal surveys—in astronomy and astrophysics, planetary science, life and microgravity science, and solar and space physics—a review of the goals and direction of the U.S. human exploration program, a prioritization of NASA space technology roadmaps, as well as reports on issues such as NASA's Strategic Direction, orbital debris, the future of NASA's astronaut corps, and NASA's flight research program. Before joining the SSB and ASEB in 2010, Dr. Moloney was associate director of the BPA and study director for the decadal survey for astronomy and astrophysics (Astro2010). Since joining the NRC in 2001, Dr. Moloney has served as a study director at the National Materials Advisory Board, the Board on Physics and Astronomy (BPA), the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Dr. Moloney has served as study director or senior staff for a series of reports on subject matters as varied as quantum physics, nanotechnology, cosmology, the operation of the nation's helium reserve, new anti-counterfeiting technologies for currency, corrosion science, and nuclear fusion. In addition to his professional experience at the Academies, Dr. Moloney has more than 7 years' experience as a foreign-service officer for the Irish government—including serving at the Irish Embassy in Washington and the Irish Mission to the United Nations in New York. A physicist, Dr. Moloney did his Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics.

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Acronyms and Abbreviations

A	affordability
ACE	Aerosol-Cloud-Ecosystems (missions)
ACRIMSat	Active Cavity Radiometer Irradiance Monitor Satellite
AMSU	Advanced Microwave Sounding Unit
AO	Announcement of Opportunity
AR	autoregressive
AR5	Fifth Assessment of the IPCC
ARCM	*Assessing the Reliability of Complex Models* (report)
ASCENDS	Active Sensing of CO_2 Emissions over Nights, Days, and Seasons
ATLAS	Advanced Topographic Laser Altimeter System
ATMS	Advanced Technology Microwave Sounder
AWS	automated weather station
B	benefit
BSRN	Baseline Surface Radiation Network
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CEOS	Committee on Earth Observing Satellites
CERES	Clouds and Earth's Radiant Energy System
CH_4	methane
CIESIN	Center for International Earth Science Information Network
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CMIP	Climate Model Intercomparison Project
CNES	Centre National d'Études Spaciales
CO_2	carbon dioxide
CRF	cloud radiative forcing
DESDynI	Deformation, Ecosystem Structure, and Dynamics of Ice

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DSCOVR	Deep Space Climate Observatory
ECS	equilibrium climate sensitivity
ECV	essential climate variable
ENSO	El Niño southern oscillation
EOS	Earth Observing System
ERBE	Earth Radiation Budget Experiment
ERF	effective radiative forcing
ESA	European Space Agency
ESD	Earth Science Division
ESSP	Earth System Science Pathfinder
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EV	Earth Venture
EVI	Earth Venture-Instrument
EVM	Earth Venture Mission
EVS	Earth Venture Suborbital
FY	fiscal year
GCOS	Global Climate Observing System
GEDI	Global Ecosystem Dynamics Investigation
GEO-CAPE	Geostationary Coastal and Air Pollution Events
GIA	Glacial Isostatic Adjustment
GNSS	Global Navigation Satellite System
GOSAT	Greenhouse gases Observing Satellite
GPM	Global Precipitation Measurement
GPS-RO	GPS-Radio Occultation
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment Follow-on
GRUAN	GCOS Reference UpperAir Network
GSICS	Global Space-based Intercalibration System
HyspIRI	Hyperspectral Infrared Imager
I	importance
ICESat	Ice, Cloud, and land Elevation Satellite
ICESat-2	Ice, Cloud, and land Elevation Satellite-2
IDPS	Interface Data Processing Segment
InSAR	interferometric synthetic aperture radar
IPCC	Intergovernmental Panel on Climate Change
IR	infrared
ISRO	Indian Space Research Organization
JPSS	Joint Polar Satellite System
JPSS-2	Joint Polar Satellite System-2
LDCM	Landsat Data Continuity Mission
LW	longwave
MOD	merged ozone data

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MODIS	Moderate-Resolution Imaging Spectroradiometer
MSU	Microwave Sounding Unit

NAC	NASA Advisory Council
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data, and Information Service
NISAR	NASA-ISRO synthetic aperture radar
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRA	NASA Research Announcement
NRC	National Research Council

OCO	Orbiting Carbon Observatory
OCO-2	Orbiting Carbon Observatory-2
OIB	Operation IceBridge
OMPS-L	Ozone Mapping and Profiler Suite Limb
OSSE	Observing System Simulation Experiment

PACE	Pre-Aerosol, Clouds, and Ocean Ecosystem
PMOD	Physikalisch-Meteorologisches Observatorium Davos

Q	quality
QBO	quasi-biennial oscillation
QESO	quantified Earth science objective
QuickSCAT	Quick Scatterometer

RBI	Radiation Budget Instrument
ROSES	Research Opportunities in Space and Earth Sciences
RSS	Remote Sensing System

S	success probability
SAGE III	Stratospheric Aerosol and Gas Experiment–III
SAR	synthetic aperture radar
SBUV	Solar Backscatter UltraViolet
SCC	Social Cost of Carbon memo
SMAP	Soil Moisture Active-Passive
SMMI	Special Sensor Microwave Imager
S-NPP	Suomi National Polar-orbiting Partnership
SORCE	Solar Radiation and Climate Experiment
SST	sea surface temperature
SW	shortwave
SW CRF	shortwave cloud radiative forcing
SWOT	Surface Water and Ocean Topography
SYN	Synoptic Radiative Fluxes and Clouds

TIM	Total Irradiance Monitor
TIR	thermal infrared
TLT	temperature lower troposphere

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TOA	top of the atmosphere
TOMS	Total Ozone Mapping Spectrometer
TOPEX	Ocean Topography Experiment
TRL	technology readiness level
TRMM	Tropical Rainfall Measuring Mission
TSI	total solar irradiance
TSIS	Total Solar Irradiance Sensor
TSIS-2	Total Solar Irradiance Sensor-2
U	utility
UAH	University of Alabama in Huntsville
USGS	U.S. Geological Survey
UV	ultraviolet
V	value
VIIRS	Visible Infrared Imaging Radiometer Suite
VIS	visible
WMO	World Meteorological Organization

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