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Designing the Climate Observing System of the Future

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Key Points::
- A significantly expanded climate observing system could address major science questions and meet important societal needs
- Careful independent testing can evaluate whether proposed systems can address critical observing needs
- Future investments in climate observations offer large societal benefits and economic return on investments

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Abstract Climate observations are needed to address a large range of important societal issues including sea level rise, droughts, floods, extreme heat events, food security, and freshwater availability in the coming decades. Past, targeted investments in specific climate questions have resulted in tremendous improvements in issues important to human health, security, and infrastructure. However, the current climate observing system was not planned in a comprehensive, focused manner required to adequately address the full range of climate needs. A potential approach to planning the observing system of the future is presented in this article. First, this article proposes that priority be given to the most critical needs as identified within the World Climate Research Program as Grand Challenges. These currently include seven important topics: melting ice and global consequences; clouds, circulation and climate sensitivity; carbon feedbacks in the climate system; understanding and predicting weather and climate extremes; water for the food baskets of the world; regional sea-level change and coastal impacts; and near-term climate prediction. For each Grand Challenge, observations are needed for long-term monitoring, process studies and forecasting capabilities. Second, objective evaluations of proposed observing systems, including satellites, ground-based and in situ observations as well as potentially new, unidentified observational approaches, can quantify the ability to address these climate priorities. And third, investments in effective climate observations will be economically important as they will offer a magnified return on investment that justifies a far greater development of observations to serve society's needs.

Plain Language Summary The current climate observing system cannot address the range of important scientific and societally important climate issues. A significantly expanded climate observing system could address major science questions and meet important societal needs. Careful independent testing can evaluate whether proposed systems can address critical observing needs. Future investments in climate observations offer large societal benefits and economic return on investments.

1. The Challenge

Understanding the Earth's climate system and how it is changing is an important component for societal planning, economic health, ecological stewardship, and risk mitigation. Understanding aspects of climate including water usage (particularly in the food-producing regions of the world), extreme events such as hurricanes, heat waves and droughts, and sea level rise is important for society to thrive and offers substantial challenges for the science community. Targeted measurements exist to deal with some of these challenges, yet an observing system specifically designed to address these joint societal and scientific challenges has never been established (Dowell et al., 2013; National Research Council [NRC], 2007; Trenberth et al., 2013). Current international agreements only address coordination of climate observations; no commitments exist for building, and maintaining an effective climate observing system, although national efforts have supplied important components of a climate observing system (e.g., Diamond et al., 2013; World Meteorological Organization [WMO], 2015a). The Global Climate Observing System (GCOS), working with the Global Ocean Observing System (GOOS), has developed approaches to help coordinate existing efforts and aid in the planning of future observations. The results of extensive discussions is a set of principles and priorities for future observations, but these two international organizations lack the funding and authority to establish and manage observing systems on the scale needed to address the current needs (WMO, 2016). A well-designed suite of climate observations has the potential, in conjunction with appropriate models, to better characterize key processes, to resolve outstanding climate questions, and to improve the accuracy of seasonal to interannual climate predictions and multi-decadal climate projections.

Observations to satisfy curiosity are not the goal of this article. Rather, it lays out what is required of a climate observing system that addresses the essential science questions. Careful analysis leads to developing an international climate observing system, analogous to the current international weather observing system; a rigorously designed system with international commitments to provide vital surface-, in situ-, and space-based observing system components.

1.1. Motivation

Climate influences many aspects of society, economics, and the environment. The increase in population and development of agriculture, infrastructure—including buildings, electrical generation, transportation, and water delivery systems—requires appropriate estimates of the future climate. An effective observing system will lead to improved understanding of environmental resources and will allow for robust planning of critical infrastructure. Because the economic risks for climate change are measured in trillions of dollars, an observing system, with commensurate investments in science and understanding, has the potential to be of tremendous value to society if properly designed (Cabrera et al., 2007; Katz & Murphy, 1997; Keller et al., 2004; Nordhaus, 1994).

Well-designed observations serve a number of roles. The primary benefit from climate quality observations is a better understanding of Earth's climate system, whether at the process level of particular components (atmosphere, ocean, land, cryosphere) or interactions among the components, with a characterization and an adequate quantification of the scientific uncertainties. Observations set the stage for initializing and testing climate models to enable predictions and projections on various time scales (e.g., subseasonal, seasonal, interannual, decadal, centennial) (National Academies of Science [NAS], 2016). For example, global observations of the subsurface ocean improve the predictions of anomalies or extreme weather on decadal timescales. Sustained global observations will also aid in understanding the Earth system across the weather-climate interface (e.g., seasonal and interannual phenomena), allowing for societal planning on a large range of timescales.

The potential for changes to climate with large impacts is one of the major risks to modern society and understanding the likelihood of future changes is one of the greatest science challenges of this century (e.g., Intergovernmental Panel on Climate Change [IPCC], 2014; USGCRP, 2014). The approaches to addressing it include mitigation, adaptation, and potential responses such as geo-engineering (IPCC WG1, 2013, chap. 7). Mitigation includes decreasing emissions of heat-trapping greenhouse gases such as carbon dioxide or altering other forcing mechanisms such as emissions of aerosols, or stopping and even reversing deforestation. Adaptation involves planning for and reacting to the consequences. Geo-engineering approaches posit mechanisms to alter climate so that some heat balance impacts could be lessened. Continuous, comprehensive global observations would help to address the fundamental gaps in science and to quantify the attendant uncertainties with respect to any of these three approaches. Better baseline information about the current Earth system leads to improved understanding of potential impacts of, for instance, solar geo-engineering approaches, to Earth's hydrologic cycle and regional climates.

Climate change is but one example of the need to make decisions under deep uncertainty. Developing new approaches to decision making that go beyond traditional point and probabilistic predictions is the focus of a new scientific undertaking (e.g., see www.deepuncertainty.org). Developing adaptation pathways that will be robust under many possible futures will in part require observing systems that are designed with these needs in mind.

Recent studies (Cooke et al., 2014, 2016; Hope, 2006, 2014) have estimated the economic value of such a system at ~$10 trillion dollars to the world economy in today's value (known as "net present value" in economics using a 3% discount rate). In the simplest sense, this is the economic value of moving climate scientific understanding forward 15–20 years by using better observations, analysis, and modeling capabilities. The studies further estimated that if the world tripled its current economic investments in climate research (observations, analysis, modeling) to achieve such an advanced observing system, the return on investment would be ~$50 for every $1 invested by society. Few investments approach such return. Compare that message to the current situation of a zero-sum economic game in climate observations: one unresolved science question struggles for funding against another—both critical to achieve. The question should change from "Which critical climate science observation is more important?" to instead "What is the right amount to invest in climate research?" and its corollary "Which observations have the largest economic return on investment?".

1.2. Current Approaches to Climate Observations

Monitoring the Earth system is a major responsibility of national agencies and is coordinated through international bodies such as The Global Climate Observing System (GCOS), Committee on Earth Observation Satellites (CEOS), Coordination Group for Meteorological Satellites (CGMS), and WMO's Global Atmosphere Watch (GAW). The CGMS promotes coordinated operation and use of data and products from its members' satellite systems, in support of operational weather monitoring and forecasting, and related aspects of climate monitoring and coordinates with GCOS. However, disruptions in observing systems and the use of systems not designed for climate observations have significantly increased uncertainties in climate records, hindered progress in or increased uncertainty in key climate science such as inadequate aerosol radiative forcing and cloud feedback observations to constrain climate feedbacks and sensitivity and uncertainties in upper air trends based on weather observations (e.g., Free et al., 2002). Understanding future climate is increasingly valuable to the economies of the world and the health of the Earth (IPCC, 2013; USGCRP, 2014). However, uncertainties in projections of the future climate are large; and progress in advancing our understanding is, in many cases, limited by the observations available, for instance in ocean circulation rates and century scale global temperature records limit our ability to understand natural variability and global changes. The IPCC AR5 report evaluates the uncertainty in equilibrium climate sensitivity (ECS) based on the Climate Model Intercomparison Project (CMIP) climate models, perturbed physics ensembles of climate models, modern climate observations, and paleontological climate observations. The report concludes that ECS ranges from 1.5°C to 6°C with a confidence bound of 73% (17th to 90th percentile) and from 1°C to 6°C with a confidence bound of 85% (5th to 90th percentile). Thus, confidence in climate sensitivity (amount of global temperature increase for a doubling of CO_2 level) remains uncertain at a factor of four, while the ultimate economic impacts scale as the square of the amount of warming: or in the long term roughly a factor of 16 (Interagency Working Group on Social Cost of Carbon [IWG-SCC], 2010).

Past and existing climate observing systems have often been focused on a single observing question and, in many cases, have been driven by engineering developments. Often, these systems have been designed for other purposes such as weather prediction, land resource management, agriculture, air pollution, or other operational and research topics, resulting in suboptimal climate observations. Individual efforts to assess the value of added observing systems have often advanced in an ad hoc manner, focusing on just one aspect of the Earth system. The results have increased our knowledge in specific areas, but with too little coordination to allow continued and rapid improvements in our comprehensive understanding of the integrated climate system.

While existing observations are undeniably valuable and cost effective, they are far below the capabilities we envision for an advanced climate observing system. Limits today are primarily economic and not technological. In this context, an improved climate observing system is fundamentally an investment for the benefit of society. This investment is urgent, especially given the long-time scales of both climate and societal policy actions. The Cooke et al. (2014) economic value study estimated a $650B per-year cost (net present value, 3% discount rate) to society for every year we delay an advanced climate observing system. At the same time, it is important to prioritize and estimate the costs and benefit of improvements if society is to invest in an improved climate observing system as opposed to a zero-sum game of "business as usual" and "do the best you can," or the even worse scenario of de-vesting in observations. As an example, important observation sites in the Arctic, tropical Pacific moorings and even GCOS' Reference Upper Air Network sites are decreasing, due primarily to budgetary constraints. The current approach has failed to significantly narrow uncertainty in climate sensitivity even after 35 years of effort. This can be seen by simply comparing the discussion of climate sensitivity uncertainty in the *Charney Report* (NRC, 1979) to the recent IPCC AR5 (2014). Advances in our understanding of the complexity of the Earth system will likely be slow if we do not have a significantly improved observing system that will allow for investigation of specific aspects of the feedbacks in the climate system (Trenberth et al., 2013; Wielicki et al., 2013).

GCOS, which was created in 1992 as a result of the Second World Climate Conference, has helped identify priorities (Karl et al., 2010; Manton et al., 2010) and coordinate some climate observations with the identification of the "essential climate variables" (ECVs) (National Centers for Environmental Information, 2017; WMO, 2015a, 2015b, 2016). The ECVs, developed in a pragmatic way, take into account the past record and capabilities as well as the needs, and may not include some climate variables regarded as vital but for which there is no current capability. In addition to assessing the ECVs, GCOS has also highlighted the value of reprocessing and reanalysis of variables to produce consistent homogeneous datasets (see also Trenberth et al., 2013). For most of these ECV's, continuity of observations and appropriate overlap with any new observations will be crucial for developing well characterized long-term datasets.

The role of the ocean is increasingly understood to play a major role in climate and more specifically in the World Climate Research Program's (WCRP) Grand Challenges. Essential Ocean Variables (EOVs) (http://goosocean.org) if fully implemented, could help address many of the uncertainties in the role of oceans in climate. WCRP's Climate and Ocean: Variability, Predictability and Change (CLIVAR) has developed and tested hypotheses for ocean observations with explicit goals of developing parameterizations that can go into climate models. Deep Ocean Observing System with their plans for Deep Ocean Observations, if fully supported, will likely make significant progress in providing data that will help improve projections for all of the current Grand Challenges and may particularly help in improving long-term forecasting, understanding regional sea level rise, extreme events, and water availability (Heinbach et al., 2014).

The difficulty of achieving a more effective observing system is considerable. Coordination across disparate research communities with only modest or minimal overlap poses a major challenge. These communities are focused on surface- and in situ-based climate observations, satellite-based climate observations, climate modeling and projection science, attribution, economics of climate impacts, and climate policy. In the U.S., the USGCRP is currently the only major organization charged with such a broad charter. Internationally, the WCRP coordinates research for climate, while the intergovernmental group on Earth observations (GEO) coordinates efforts on all Earth observations. GCOS serves as a system of systems with a more narrow focus, but it works with WCRP to further climate-related goals. Ultimately, the best vision is one that can be effective at both national and international levels, one that involves global observations of the Earth system. The challenge is made more difficult by the complicated, individual budgetary structures and operations of coordinating bodies such as USGCRP, WCRP, GCOS, GEO together with the individual national agencies. This disparate decision-making process prevents a coordinated clear vision for a climate observing system that benefits society, can be broadly supported by scientific leadership, and can be implemented by national and international efforts.

A more rigorously planned observing system would require that the future observations be organized and evaluated around clear, testable hypotheses that consider the full Earth System with quantifiable performance measures for science and society. It would be beneficial to categorize current and future observing systems according to how they serve particular quantified climate goals and societal needs. Such goals could closely align with the USGCRP research goals, WCRP Grand Challenges, and IPCC major uncertainties identified in the Working Group I assessments. The final result would be an observing system that focuses efforts on societally important challenges and achieve quantifiable results.

The current article focuses on two key aspects of the above observing system design elements: quantified science objectives and critical evaluation of proposed observations. The prioritization of science objectives and the critical evaluation of proposed approaches would provide a critical element of moving from qualitative objectives in support of climate exploration-driven science toward quantitative objectives in support of hypothesis- and societal benefit-driven climate science. This would not be the first time that a focused scientific effort resulted in important scientific insights. In particle physics, the Standard Model provides the theory to set the design of high-energy particle accelerator observation requirements such as the recent search for the Higgs Boson particle using CERN's Large Hadron Collider. For climate, integrated Earth system models replace the Standard Model for hypothesis development and testing. There is no "parallel" Earth on which to experiment; instead state-of-the-art numerical models representative of the climate system are a critical platform for integrating all known affects and affirming/nullifying hypotheses. These climate models are highly dependent on available observations to incorporate the chemical, physical, biological and ecological processes of the Earth accurately.

1.2.1. Coordination of Activities

There are four major climate observation assessments relevant to defining and prioritizing climate observations and their goals.

In 2012, the U.S. completed the first national Earth Observation Assessment to identify available observing capabilities. The effort helped establish a baseline for existing observations, but not a path forward for future observations or priorities. A follow-on effort worked to identify priorities across 13 societal benefit areas, where climate is only one of those areas.

Second, NOAA has recently carried out a NOAA Observing System Integrated Analysis (NOSIA-II) (Reining et al., 2016). This analysis is somewhat similar to the EOA and follow up activities' approach of assigning priorities to existing services and products with a subjective evaluation of their impact or value (e.g., a qualitative Priority 1 through 5 NOSIA-II does use some observing system simulation experiments (OSSEs) for weather in a very limited way, but does not for climate observations).

Third, the WMO/WCRP/GCOS documents survey current and planned observations and their value to climate science, including suggested requirements for accuracy and sampling. These recommendations are primarily for continuity of existing capability as opposed to an attempt to design the observing system required to achieve climate science quantified objectives. Requirements are back-of-the-envelope estimates in most cases (Ohring et al., 2005). The GCOS (WMO, 2016) also identifies ~50 essential climate variables. While these variables have not been defined using rigorous evaluations, they offer subjective selections based on current observation capabilities which can be tested in a more formal sense for achieving identified climate goals.

Fourth, COSPAR has prepared a new assessment and recommendations: "Observation and integrated earth system science: a roadmap for 2016–2025." (COSPAR, 2015; Simmons et al., 2016). It focuses on the combined use of observations and modeling to address the functioning, predictability, and possible evolution of the Earth system on timescales out to a century or so. It discusses how observations support integrated Earth system science and its applications, and identifies planned enhancements to the contributing observing systems and other requirements for observations and their processing. However, it offers little prioritization of the broad range of climate observational needs, focuses only on the coming 10 years and primarily highlights the role of space research in climate observations.

These assessments are, by design, limited in their scope, but have provided valuable experience that can help guide a more comprehensive evaluation of climate observing systems. We conclude that no existing or near-term studies are designed to define the required climate observing system, one that also factors in the economic value to society. A number of entities, including GCOS, WCRP, USGCRP, and NRC could step forward to define quantified climate science objectives as the key starting point of defining an advanced climate observing system, but this would require sufficient studies to understand the true requirements. Once quantified objectives are decided, the next natural step is to quantify observing system capabilities using rigorous quantifiable approaches. The specific approach will vary with science objective, available data and with the maturity of any proposed climate models or climate model processes.

Lessons from past observations on quality, coordination, calibration, data access and continuity would be applied to any new observations, because these key attributes directly affect the successful use of climate observations. These lessons can be augmented with more thorough evaluations of how observing systems will be used to achieve their stated goals.

1.3. Past Investments Have Benefitted Society

Large investments in our current observing system have resulted in a significantly improved understanding of societally important services including food, water, energy, transportation, human health and safety. The combination of satellite, ground-based, and in situ measurements, particularly when multiple instruments are used in combination, has given us tremendous insights into the Earth system. Of particular note is the progress that has been made in understanding and predicting the aspects of the Earth that are most crucial to human activity: water, food production, and health. Some of the many examples of important advances in our understanding that are directly due to our successful observations include:

1. Our improved understanding of sea level rise, measured better than in the past, from regional to global scale, using satellite altimetry since the 1992, along with improved understanding of impacts of El Niño/Southern Oscillation variability on coastal regions, has allowed for a better understanding of the need for resilience in the planning of future coastal infrastructure (Fu & Cazenave, 2000).
2. The documentation of the ozone hole, its growth, stability, and now slow recovery, allowed decision makers to work internationally to avoid the most serious impacts of increased ultraviolet radiation including increased crop failure and cancer rates (WMO, 2015b).
3. Melting sea ice has been measured since the 1970s by passive microwave sensors allowing a full understanding of the spatial extent and rate of sea-ice loss across the Arctic (Stroeve et al., 2014).
4. Melting land ice has been measured by interferometric Synthetic Aperture Radar, altimetry, and the Gravity Recovery and Climate Experiment: monitoring since the 1990s (sparse), boost in 2002 (GRACE), extended following IPY (2007) and Landsat/Sentinel (2013) has given us previously unattainable insight into how much water is going into the oceans from storage in land ice (Rignot et al., 2013; Velicogna et al., 2014).
5. Careful measurements of CO_2 have given us a solid understanding of the global increase in carbon over the past six decades; verification of this rise has allowed a more informed understanding of the impact of greenhouse gases on the environment (Le Quéré et al., 2015).
6. Underwater measurements of ocean temperature, salinity, and pressure from ARGO floats have given us unprecedented understanding of how the surface of the ocean relates to the full ocean boundary layer in a very cost effective manner (Roemmich et al., 2003).
7. Increasing number of observations and steady monitoring of tropospheric and stratospheric aerosols over the past four decades has yielded quantifiable understanding of the global distribution of atmospheric aerosols over time, in turn improving the confidence in the estimates of the radiative forcing due to these species, including areas where they pose serious hazards to air quality and human health (IPCC WG1, 2013, chaps 6 and 7).

In each case, the investment in observations has resulted in societal decisions that have had large economic returns, likely far beyond the cost. We recognize that this advance in our understanding has been due to the careful planning of observations, the insightful analysis of observations, and the international effort to appropriately interpret all climate science results. The lessons learned from each success story need to be carried forward to the planning of future climate observations.

1.4. Remaining Uncertainties

Despite the large advances in our climate observations, we now recognize societally and scientifically important questions that cannot be addressed with our current observing system. Across the Earth system literature, specific uncertainties have been highlighted in peer-reviewed journals as well as assessments. A few examples include:

1. Climate sensitivity and cloud feedbacks are one of the largest uncertainties in the climate system and yet, our understanding is still limited by accuracy and resolution of the radiation and cloud-property observing system for long-term trends, as well as a range of atmospheric state variables for cloud process studies (Bony et al., 2015; IPCC, 2013). Variation and changes to stratospheric aerosols, circulation, and modes of variability, and their impacts on global radiative forcing and tropospheric processes remains poorly understood (Solomon et al., 2011).
2. Understanding the loss of Arctic sea ice and the extent that it is affected by boundary layer atmospheric phenomena or under-ice ocean observations — both of which are not observed well in the Arctic — remain difficult to understand. Arctic sea ice is critically important to local environments, indigenous lifestyles, global circulation, and transportation through the Arctic (Vihma, 2014).
3. Precipitation extremes on a range of timescales and our currently poor ability to monitor them prevent us from understanding and predicting droughts and severe floods (Hou et al., 2014). Understanding both temperatures over the ocean and air-sea interactions is critical to forecasting flooding events and seasonal precipitation (Chang et al., 1997).
4. Understanding the full dynamics of the ocean and its role in the Earth's climate, ocean heat storage and the uncertainties in regional sea level rise of the 21st century are currently limited by a lack of understanding of ocean circulation and chemical exchange between the air and the ocean (Bamber & Aspinall, 2013).
5. Impacts of water management for agricultural and energy usage require better understanding of seasonal forecasts (Viala, 2008).
6. Understanding carbon fluxes on a continental scale is currently challenged by a lack of high-quality, detailed observations. Such an understanding could help identify regions of carbon uptake and regions where energy choices are having a positive impact (Bruhwiler et al., 2017).
7. Seasonal forecasts of the fundamental water, energy, and carbon cycles are needed to support societal uses of these resources (MacLachlan et al., 2015; Saha et al., 2014).

The current observing system and coordination of activities are not able to address these and many other societally important questions about the Earth system.

Without clarification on these issues, planning for future development, including coastal infrastructure, national energy plans, and regional freshwater allocations are all made with an unnecessarily high level of risk. Addressing the most important observational gaps needs to take place in a coordinated manner. The result will be an effective observational system that can reduce uncertainties for the most societally important climate questions.

2. Prioritizing Observational Needs

For critical climate science questions, some groups have already organized thoughts and identified priorities for climate research. The IPCC WG I report (2013), GCOS, Committee on Space Research (COSPAR), and other groups have worked to identify priorities.(COSPAR, 2015) The WCRP codified these priorities as seven Grand Challenges: clouds, circulation and climate sensitivity; melting ice and global consequences; climate extremes; regional sea-level change and coastal impacts; water availability; carbon cycle and seasonal forecasts. Further progress may be obtained through the USGCRP or through the currently active NASA/NOAA/USGS 2017 Earth Science Decadal Survey. Unfortunately, to date, goals often express qualitative understanding of needs as opposed to quantitative hypothesis testing. The 2017 Earth Science Decadal Survey embraces the community's preference by requesting quantitative science and application objectives in their second open Request for Information or RFI-2, but focuses only on satellite observations. Similarly, GCOS has started identifying quantitative observational needs in terms of stability, coverage and accuracy (WMO, 2016).

A new organization of observational priorities will help decision makers, researchers, and instrument developers understand what observations are available, being planned, needed or under evaluation. Observations that can serve the WCRP's Grand Challenges can be prioritized and comparisons can be made to different observing options for supporting any of these Grand Challenges as illustrated in Figure 1.

Instead of discussions around, for instance, satellite priorities, this structure encourages discussions around important scientific questions: the best observing system can be chosen across all possible platforms or combination of approaches. The structure also acknowledges that at least three categories of observations are needed, including observations that help improve forecasts and projections of the climate system, observations that allow improved understanding of processes and long-term monitoring observations. Each category may require different specifications for critical parameters. Individual observing systems may serve multiple climate goals in this structure, as well as other scientific or societal goals such as supporting weather forecasts. Significantly, WCRP Grand Challenges are re-evaluated and may be augmented over time, as society's priorities change, so this proposed structure can be resilient to changing demands of the climate community.

With a structure, as summarized in Figure 1, the scientific community can identify the critical goals under each category of observational needs and possible observational sources can be identified. The identification of the needs, irrespective of what existing capabilities are, can spur innovation and help assure that observational investments respond to critical science questions. It is vital for the utility and economic value of observing systems that the evaluation of proposed observations be considered across all platforms and that the evaluation can be applied to proposed observing systems not yet in existence. In the past two decades observational capabilities have emerged that had not been previously taken seriously for systematic Earth observations: radio occultation measurements; observations from both small and large unmanned aircraft and the use of citizen scientists addressing formidable observational challenges (Kursinski et al., 1997; Silvertown, 2009; Watts et al., 2012). Particularly for the more novel, emerging approaches, objective evaluation will be critical to making the best investments in observations of the future. Innovative observational advances can be encouraged and appropriately employed by making the climate observational needs clear and quantified.

Once scientific requirements and recommendations are made and possible observational approaches are identified, individual agencies will likely address additional considerations in making specific choices. These considerations may include costs, timeliness of execution, and likelihood of success (NRC, 2015).

The new observing system will form the basis for research and applications of the research which involve working to:

1. Develop testing to assure observations will be effective
2. Develop and improve analysis and processing methods to produce timely products for multiple uses (some of which might be transitioned to the private sector)
3. Develop climate services to disseminate information and actively solicit feedback on evolving user needs
4. Carry out comprehensive evaluations of the observing system and make recommendations on how to improve it and cut costs
5. Evaluate the success of the observations based on their support of societally relevant information, including climate services and information that can improve predictions and projections of climate

As long as the efforts between different national agencies remains coordinated, the investment in observations will likely result in actionable information for society with minimal waste in investments. Both economic considerations and the need for continuous records will likely dictate that the new observing system will build appropriately from the current observations.

2.1. Baseline Information, Continuous Records and Independent Verification

Researchers and decision makers have long valued the need for good baseline information and continuous records from all observing systems, even as technologies and monitoring approaches change (e.g., Mitchell & Jones, 2005; Seidel et al., 2009; Wulder et al., 2011). Discontinuities of observations add tremendous uncertainty to both the observations reported and the derived trends because of the difficulty in addressing disruptions (Free et al., 2002; Weatherhead et al., 2017). The National Academies of Sciences, Engineering and Medicine convened a panel to address continuity of Earth observations from space. The results are summarized in the published report, "Continuity of NASA Earth observations from space: a value framework" (NRC, 2015). While the focus of this report was on planning and evaluating NASA observations, many of the results have general application to all Earth observations and have great

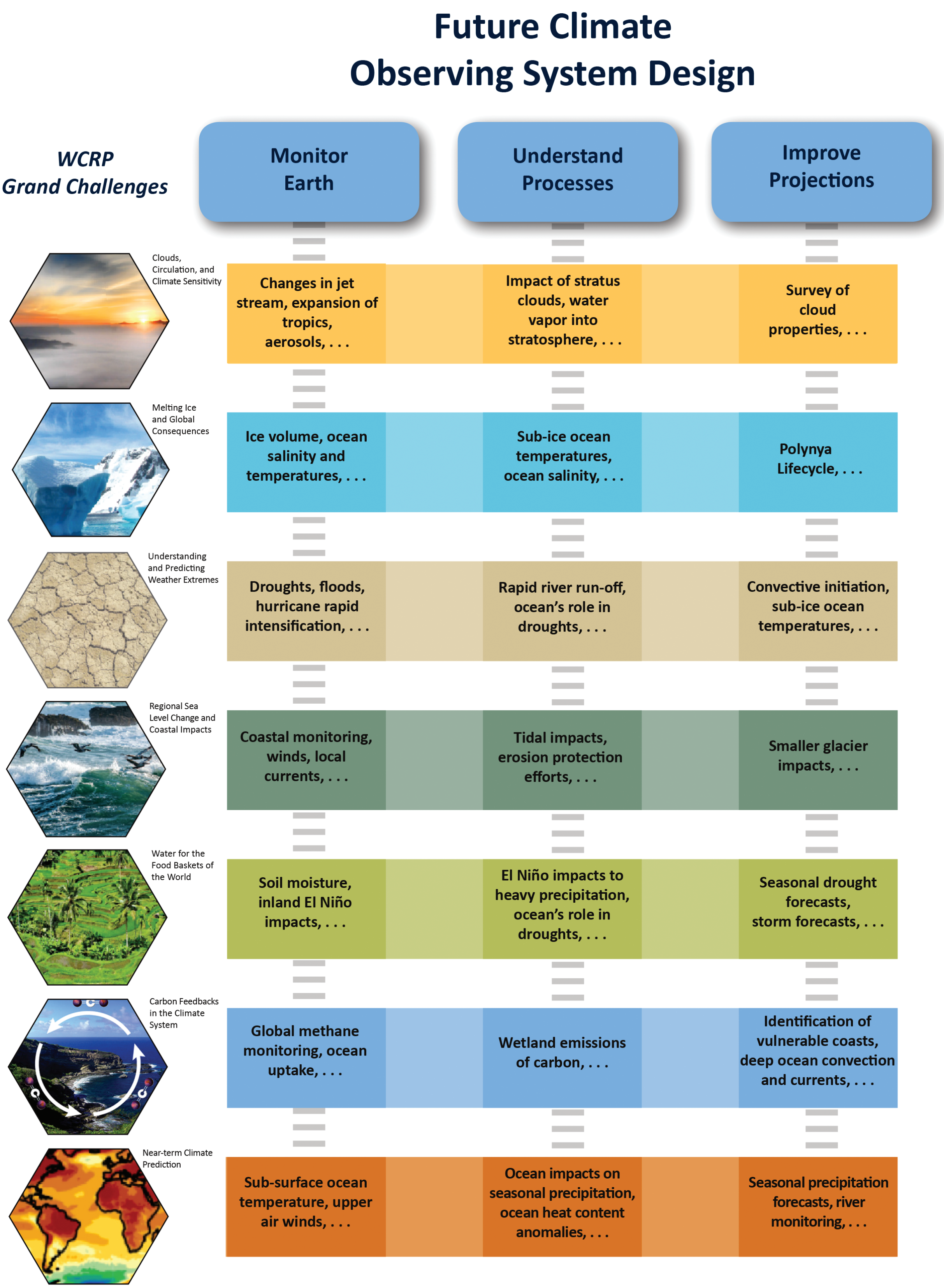

Figure 1. Proposed organizational structure to compare and evaluate existing and proposed observing systems. Note that the categorization is based on whether observations serve testable hypotheses or quantifiable goals, as opposed to categorization by agency; or by platforms (satellite, in situ, and ground-based). The items listed in the boxes are examples of possible scientific goals for that category and are not meant to indicate the most important goals.

overlap with the goals of this document. The report identifies societal benefit as a major motivation for collecting observations, with four major aspects of benefit defined as: importance, utility, quality, and success probability:

1. The scientific importance of achieving an objective.
2. The utility of a geophysical variable record for achieving an objective.
3. The quality of a measurement for providing the desired geophysical variable and.
4. The success probability of achieving the measurement and its associated geophysical variable record.

In addition to these four major aspects, affordability is added as a discriminator in evaluating proposed observing systems. The evaluation of affordability can be addressed relative to the added value of attaining the specific goal. As an example, improving long-term forecasting — one of the WCRP Grand Challenges — can offer tremendous societal value: weather impacts to the economy have been estimated to exceed $450 billion per year in the US, not including the impacts of severe storms (Lazo et al., 2011). Weather events, particularly costly extreme events need to be evaluated in the context of climate change; this includes heat waves, droughts, floods, Arctic summer sea-ice extent and thickness, severe storms, hurricanes and so on. The weather-climate interface becomes an important crux of scientific understanding leading to predictions, and juxtaposes the boundary-value problem in climate with the initial-value problem involving the Earth system. The combined significance of the atmosphere, land, ocean, chemistry and ice observations poses an additional challenge in characterizing the uncertainties. A coordinated observing system can support progress in the understanding of these multi-disciplinary challenges by requiring the observational needs to be developed jointly across multi-disciplinary communities.

Because societal decisions based on climate observations may be large and potentially expensive, climate observations and conclusions based on those observations need to be independently verified. In some cases, this verification will involve independent high-level calibration of the instrumentation; in other cases, the focus will be on independent observations to assure appropriate interpretations. Peer-reviewed literature review and international assessments will be important for the interpretation of observations and development of appropriate model results. Just as importantly, observational systems will need to be evaluated after implementation to assure they met their stated goals and help understand any shortcomings or unexpected benefits that will benefit further observing system planning.

3. Quantitative Evaluation of Observations

Critical to improving the observing system is improving the rigor with which planned observations are quantifiably linked to clear science objectives. Climate OSSEs can identify the usefulness of different measurements needed to achieve the science goal or question, with specific input to the elements in the list above. OSSEs and observing system experiments (OSEs) have a long history for Numerical Weather Prediction (Atlas, 1997; Atlas et al., 2015, 2015; English et al., 2017; Peevey et al., 2017) and have been utilized to study the ocean (Halliwell et al., 2014; Oke et al., 2015). OSEs and OSSEs use a data assimilation system that is run with and without a particular set of observations to assess their impact, possible biases, and other issues. OSEs evaluate current observing systems and are routinely performed when new observations come on line (especially from a new satellite), while OSSEs can simulate potential future observing systems. Climate OSSEs, or COSSEs, are a set of approaches that estimate the value of a set of observations to address a particular science question, given the inherent variability, measurement uncertainty, and confounding factors. The use of OSSEs for climate applications are still being developed, and the climate research community can improve the soundness of investments in future observations by developing more COSSE capabilities (Cooperative Institute for Research in Environmental Sciences, 2017a). As the variety of science questions is broad, so are the types of approaches to evaluate proposed observations.

Simulating the effects of climate observations has been a part of planning of development of Earth observing systems. In recent years, there is a strong desire to make these efforts more rigorous to assure the effectiveness of future observations (Weatherhead et al., 2002, 2017). Notable COSSE efforts have included ocean heat content (Argo) (Abraham et al., 2013), carbon cycle sources and sinks, (OCO-2 and CarbonTracker) (Basu et al., 2013) temperature trends using radio occultation, (COSMIC) (Ho et al., 2009) and cloud feedbacks (CLARREO/CERES) (Shea et al., 2016). Most of these COSSEs have focused on decadal change measurements, but some involve climate processes (OCO-2, CALIPSO). COSSEs can evaluate many aspects of climate observations, ranging from instrument accuracy requirements (Wielicki et al., 2013) to estimations of retrieval uncertainty (Connor et al., 2008) and sampling uncertainty (MacDonald, 2005). Quantification of such requirements is important to evaluating cost versus benefit for a climate observation. Unfortunately, many climate observation programs have yet to develop COSSEs to independently test the capabilities of proposed observations at addressing critical goals. Such development is not trivial. The examples given above suggest a typical 2- to 3-year time scale to develop a COSSE capability using an integrated team of modeling and observation expertise. There is value both for standing COSSE groups to support decisions and broad research efforts on evaluation techniques to continue the development of the science needed to support strong, reliable results.

Designing an advanced and more rigorous international climate observing system would be a challenge in itself that should address the following key elements:

1. Define quantified science goals or questions
2. Identify the key variables or groups of variables needed to address the critical science questions
3. Quantify the spatial coverage and resolution required to address the science questions
4. Quantify the temporal duration and resolution required to meet the science requirements
5. Quantify the accuracy or quality of the measurement needed to achieve the science goal (e.g., calibration, orbit or surface sampling, and algorithm uncertainties)

These design elements have sometimes been addressed individually by proponents of specific observing systems, but have not been applied uniformly to ensure impartial assessment of usefulness. A formal evaluation effort would allow for the critical comparison of different systems based on similar criteria and incorporating realistic variability, albeit with assumptions related to the appropriateness of the model used.

COSSEs can be used to address the three major climate observing system elements represented as the three independent columns in Figure 1: climate monitoring, climate process understanding, and climate prediction uncertainty. In most cases, the proposed observation is simulated either while running the underlying physical climate/process model or using climate/process model output. In some cases, COSSEs of potential new observations can be developed as a combination of existing observations and theoretical models. An example of this method is the case of remote sensing COSSEs using current observations plus radiative transfer models to simulate future remote sensing observations from space. Some aspects of COSSEs are highly model-dependent, particularly when COSSEs are used in a method of reanalysis or when global climate models are used to identify sensitivities to specific parameters. For these reasons, model-independent COSSE efforts will be used as often as possible to support the appropriate observational capabilities.

While many COSSE examples tend to use one or at most a few underlying climate, weather, or process models, ultimately COSSEs can more rigorously examine the usefulness of observations in quantitatively constraining model physics by using a variety of approaches including perturbed physics ensembles (PPEs). In this case, Bayesian approaches can quantify the relationship between observing system capabilities and uncertainties in key model parameters. This approach has been used in many research fields and is well documented in the NRC report "Assessing the reliability of complex models" (NRC, 2012) which also summarizes the limitations of using Bayesian approaches. Where applicable, the Bayesian approach could be a long-term goal of more rigorous understanding of climate observing system requirements. The increased human and computer resources required to process, store, and analyze a large number of COSSE simulations with the Bayesian approach poses a major challenge. Developing techniques to address the seasonal, daily, and subhourly variability will require scientific investments which will likely lead to new insights about the requirements for climate observations.

While the OSSE techniques needed for evaluating such different observing requirements vary in approach, some decision-making steps are useful for all COSSE efforts: (1) a set of critical 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 (NRC, 2015). While this systems approach may be useful, it does not currently exist, in part due to the lack of coordinated planning of climate observations and common practices for evaluating proposed observing systems. The combination of COSSE results and both economic and pragmatic constraints can assure effective investments in observations. Such practices, if more uniformly employed, will allow observing system requirements to be directly related to physical hypothesis to link proposed observations to their intended use.

When applied to improving climate process observations (e.g., aerosols, clouds, chemistry), COSSEs may require very high-resolution process models, which would be too computationally expensive to run in a 100-year climate simulation. In these cases, model resolution might change from the ~100-km resolution of an IPCC Climate Modeling Intercomparison Project (CMIP) climate model simulation to 1 km of a cloud resolving model, or 5 km of a weather prediction or chemistry model. In this sense, there can be an overlap of OSSE simulations run for weather or air quality purposes and those run as COSSEs. Some of the same modeling tools can serve as either the basis of the climate process COSSE, or the OSSE output itself might be used to support a climate process COSSE. The key in these situations is the time/space resolution and the OSSE physical variables saved in the model output. As a result of this link, recent advances of weather OSSEs by NOAA (global 7-km resolution simulations) might be very useful for climate process COSSEs. Similar advances in air quality prediction OSSEs are relevant to climate process COSSEs. High-resolution regional models are also relevant as they can achieve even higher time and space resolution physics, especially for cloud systems where boundary layer Large Eddy Simulation models run at 10's of meter grid scale, or deep convective cloud resolving models run at ~1-km grid scale. In this latter case, COSSEs could be used to evaluate cloud field experiment observation requirements.

One major advantage of COSSEs that involves the use of climate models is that, by their nature, they require a close coordination and continued communication between the climate modeling community and the climate observation community. Such an advance in communication would likely lead to more rapid use and application of observations by climate models as well as a clearer understanding by observation researchers of the key technological advances needed for future observations (Weaver et al., 2013). Often a new observation technology can be like a hammer looking for a nail; this science-priority approach, together with close communication between climate modelers and observationalists, reverses this paradigm to the benefit of the science goals. Additionally, many new observations wait years before being used by the modeling community. Close coordination and communication of modeling and observation communities through COSSE efforts can lead to improved approaches to both the development and use of new technologies.

The design of climate observing systems in a thoughtful, science-driven manner can serve as an example for other large science issues with societal relevance. As described above, COSSEs provide a link between climate hypothesis tests and goals with observational capabilities. For the range of topics in the Grand Challenge, this approach could additionally support "seamless prediction" from weather to seasonal to decadal Earth system prediction. Input from COSSEs will help inform scientific decisions on identification of the optimal observing system of the future.

Equally valuable to a continually evolving observation system is the re-evaluation of the COSSE conclusions after a new observational system has been put into place (e.g., Crisp et al., 2017). The skills and usefulness of COSSEs will only evolve if the approaches are evaluated on their results. The risk of overstating capabilities either intentionally or by omission of full consideration of the proposed observing system currently hurts all climate science: the use of resources on a suboptimal system will often delay investment in alternative systems. The delay of achieving climate results has a quantifiable cost to society. Because of these concerns, retrospective analyses of how an observing system performs needs to be planned into all new observing systems, including campaigns and long-term monitoring. The analysis can compare stated and achieved goals, actual societal use of the climate products, and any cost savings or over-runs. Through objective analysis of successes and failures, and the public sharing of results, can the observing system of the future evolve in an efficient and successful manner.

3.1. Examples of Testable Hypotheses and Goals for Climate

A common misconception is that climate observations are simply weather observations over a longer period of time. The complexity of climate questions dictates sometimes very targeted observations to address a key science question or supply information for a societal goal. This article proposes that new observations be hypothesis driven or address a specific gap. Below we give a few examples of potential quantified hypotheses or goals. Without specific requirements, a well-intended observing system may not adequately to address its stated purpose.

Hypothesis: The expansion of the tropics is occurring and is directly related to climate change driving the modification of the Hadley Circulation. Determine the expansion of the tropics to within 15 km/decade at

95% confidence. Example observational requirements: daily observations of temperature (±0.2°K), humidity (±2% RH) and wind (±2 m/s) every 100 m from the surface to the mid-stratosphere over the tropics (30°N to 30°S) for three decades. Horizontal sampling and accuracy requirements to be determined using COSSEs that include data assimilation methods.

Hypothesis: Stratospheric ozone levels are increasing due to limitations in production of ozone-depleting substances. Determine ozone trends to within 1% /decade at 95% confidence interval. Example observational requirements: Observations every 3 days of stratospheric ozone levels (±2%) across all latitudes (90N to 90S) for a minimum of 20 years. Sampling and accuracy requirements to be determined using COSSEs that evaluate projected trends in light of normal stratospheric variability and measurement stability.

Hypothesis: Solar activity influences climate circulation patterns. To monitor such changes in solar radiative forcing, determine Total Solar Irradiance to an SI traceable absolute accuracy of 100 ppm and stability of 10 ppm/year (NRC, 2013). Determine Spectral Solar Irradiance to an absolute accuracy of 0.5% and stability of 0.05%/year. TSI and SSI observations sufficient to determine monthly averages at the traceable accuracy and stability indicated above.

Hypothesis: Low-level, in situ observations of the boundary layer can reduce uncertainty in climatological estimates of boundary layer winds (important for aviation turbulence and renewable energy planning) by as much as 20%, allowing for improved parameterization models. Observational requirements: Boundary layer measurements of winds (±2 m/s) at up to 24 different locations for a period of 4 years. Space and time sampling, vertical resolution, and accuracy to be determined using COSSEs that focus on regional variability in state-of-the-art weather models.

Hypothesis: Upper tropospheric temperatures are increasing at approximately 0.2°K/decade. Monitor this trend with an uncertainty of 0.08 K/decade (95% confidence interval). Observational requirements: continuous measurements of temperature (±0.1°K), from the boundary layer to the lower stratosphere, every 10 mb, (60°N to 60°S) continuously. Accuracy, vertical resolution, spatial resolution and time resolution determined using COSSE that accounts for fundamental observational uncertainties, including the benefits and uncertainties from merging multiple observational systems.

Hypothesis: Regional fluxes of carbon from the eastern half of North America are within 15% of the global average flux estimates when considered on an annual basis. Observational requirements: 3000 flask measurements per year across the Eastern U.S. for a period of 3 years. Number of flasks and locations determined by initial COSSE effort that uses weather models for integrating regional sources and transport.

Goal: Reduce the uncertainty in aerosol radiative forcing by 50%. COSSEs would be run with global climate models to identify observations needed: identify locations for surface air quality measurements and satellite requirements to establish global, non-urban pollution source estimates.

Goal: Determine the change in global ocean heat storage over a decade time scale to within 0.1 W/m^2 and over annual time scale to 0.2 W/m^2. This may require ocean vertical profile temperature and salinity measurements using a network of autonomous floats (e.g., Argo), global ocean sea level rise, global ice mass change, and global net radiative flux. COSSEs will test whether observations with accuracy of 0.1 W/m^2 will be required for at least 50 years; space and time sampling requirements will be determined using COSSEs that integrate ocean observations to the full depth observable (von Schuckmann et al., 2015).

Goal: Narrow uncertainty in equilibrium or transient climate sensitivity by a factor of two relative to the 2013 IPCC report. Observations required for 50 years. Observation requirements (aerosol radiative forcing, greenhouse gas radiative forcing, land use radiative forcing, SW, LW, and net cloud radiative forcing, ocean heat storage, surface air temperature, cloud physical and microphysical properties) based on priorities established by international efforts, and observational requirements determined using COSSEs that include global climate models and specific physics packages incorporating observed parameters.

Goal: Determine the rate of sea level rise to a global mean accuracy of 0.2 mm/year. The rate of sea level rise from ice sheet loss is likely to be nonlinear and to accelerate in a warming Earth. Observations required indefinitely. Observation requirements beyond current ocean and satellite measurements (sea level rise, ice sheet mass, ocean temperature and salinity profiles [thermal expansion], mountain glacier mass loss) determined using COSSEs that evaluate potential sea level rise given current measurement uncertainties and regional effects.

Goal: Observe or estimate solar radiation at a 1-km^2 resolution to an accuracy of 5% over a 1-h period. This is required to support renewable energy applications. Accuracy, time sampling, and space sampling requirements determined using COSSEs that simulate cloud and aerosol behavior at the 1-km level and observational uncertainty of both radiation and cloud observations. Importance based on analysis of economic value of improved capabilities.

Goal: Measure or estimate boundary layer winds, turbulence, vertical shear, and boundary layer height. This is required in support of aviation, air quality, and renewable energy with a 25% improvement over current estimates for each of these parameters. Accuracy, time sampling, space sampling requirements determined using COSSE. Importance based on analysis of economic value of improved capabilities.

The range of hypotheses and goals for climate observations means that a range of COSSE approaches will be used. In general, COSSEs will evaluate the spatial and temporal sampling requirements and accuracy required. In some cases, the COSSEs will evaluate the value added of additional data in order to optimize the network (Weatherhead et al., 2017). Some COSSEs will involve computer-intensive climate models, while others will evaluate proposed observing systems' ability to reach specific goals such as being able to detect a change of 1%. The range of types of climate COSSEs as well as some publications employing COSSEs can be viewed in Cooperative Institute for Research in Environmental Sciences (2017b).

While these are neither full proposals nor descriptions of observation plans, they serve as summary examples to show the scope and intent of examining the climate observational suite and its ability to support testable hypotheses. By posting and discussing the current, planned, and proposed systems in terms of testable hypotheses with quantifiable observational requirements, new technologies may be developed that could allow for cost-saving, innovative approaches to observational needs. Ancillary benefits of observations, such as their potential usefulness to disaster response or weather forecasting may also be identified. In almost all cases, COSSEs will help inform scientific judgment on the value of proposed observation, but final decisions will include additional information, including the pragmatic aspects of observations, likelihood of success, cost and secondary benefits.

In the quantified hypothesis tests and goals given as examples, several cases include the observations required for independent verification of results. Examples are ocean heat storage from in situ temperature and salinity profiles, radiative fluxes, and independent constraints for sea level rise due to ocean thermal expansion versus ice sheet and glacier loss. Independent observations and analysis are two key scientific principles required to verify surprises in complex systems. Given the importance of climate to societal decisions and economic impacts, such verification is a significant characteristic of a future rigorous and robust climate observing system. A similar independent verification is used for the climate sensitivity example. Independent observation, analysis, and verification should be guiding principles in the design of an international climate observing system.

All quantified hypothesis tests or goals will not be equally important. In principle, an infinite number of such tests and goals could be constructed. The importance of these tests and goals to understanding and predicting future climate, including their societal impact could be used to prioritize them. For example, an important metric might be estimated based on narrowing uncertainty in economic impact (climate sensitivity, sea level rise, or ocean acidity) or as a function of key climate science uncertainties such as those evaluated in the IPCC WGI reports (2013), such as the uncertainty in different anthropogenic radiative forcings, or different climate feedbacks. The scientific community can help identify priorities, as the WCRP has done in the development of the Grand Challenges.

4. Evaluation of Benefits

While in the past climate observations—and more generally climate science—may have been perceived as a general societal benefit ("knowledge for sake of knowledge"), we make a different point in this article—one that has been made in economic analyses and is summarized here: climate observations provide economic benefit to society because they allow for enhanced planning that can save lives, property and investments. The arguments presented indicate that climate observations and scientific analyses are not an entitlement, but an appropriate investment, that can largely succeed when coordinated nationally and internationally. Designing an observing system to meet the broad climate science needs requires

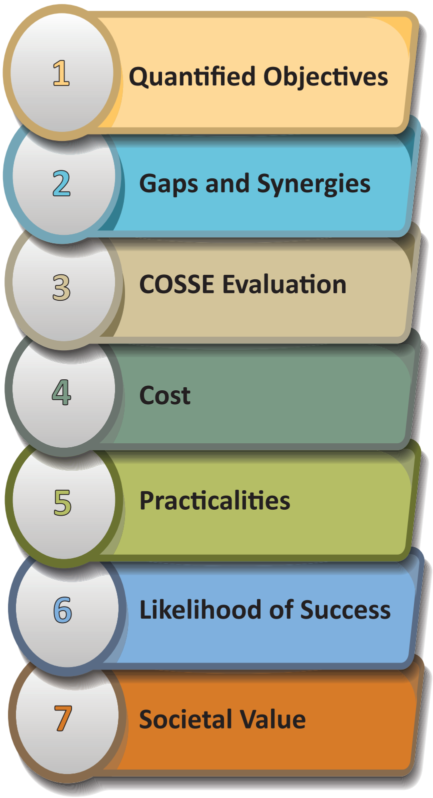

Figure 2. For each societal need, activities can be identified to specify the observing system which supports the societal impact. The goals of monitoring the Earth, advancing climate processes, and improving climate prediction can result in a robust observing system that serves science and society in a cost effective, fully justifiable manner.

thoughtful engagement of the community, building from existing efforts, and respecting current organizational structures. Carefully conceived activities can help change the paradigm for developing observing systems to support climate science from an ad hoc, sometimes engineering-driven approach to a scientifically driven set of decisions that assure appropriate investment in needed observations. We identified a number of activities that can help achieve this goal.

4.1. Societal Context for Designing a Climate Observing System

GCOS (WMO, 2016) in describing the current observing system noted, "A wide range of studies has demonstrated the cost-effectiveness of various parts of the global climate observing system." The activities to support improved climate observations described in this article can be applied to all of the Grand Challenges to help improve the effectiveness of observations to support those important goals. Specifically, quantified climate science objectives, utility of each measurement to achieve the objective, quality of the measurement required, and finally the cost and success probability of proposed approaches for an observation each need to be considered. The proposed steps for evaluating proposed climate observations are listed below in Figure 2.

Notably, climate observations without commensurate scientific activities to analyze the emerging data and advance climate models will likely not result in successfully addressing any of the Grand Challenges. The analysis of data, its use in developing improved climate processes and models, and application to the Grand Challenges is as important as the observations themselves. Without planning appropriately for observational analyses and model development, the observing system will not effectively benefit society.

It is valuable to further articulate the economic costs and benefits of improved observing and modeling of the Earth system, leading to understanding and predictions/projections. The challenges of cross-disciplinary work between economists and climate scientists are large, but there is still work to be done toward unambiguously addressing damages to life and property on time scales from storms, to interannual climate and to longer time-scale trends. This work would serve us best if built from and expanded beyond the economic evaluation of weather-related disasters (e.g., hurricanes, tornadoes) with a linkage whose quantification becomes acceptable to a large community. It would be wise for both climate scientists and economists to critically evaluate current observing capabilities, starting with existing techniques and, where necessary, to develop new techniques for evaluating the effectiveness of the observing systems to address societal priorities and scientific goals. A good starting point would be to examine past events on time scales longer than daily and weekly events and to evaluate the value and effectiveness of these systems. A quantified answer based on some "case studies" from the past, over a period during which the observed changes are robust, would benefit the communication of a coherent observing system strategy.

4.2. Economic Decisions

Assessment of the economic value of future information, the area of economics generally referred to as value of information (VOI), is well developed in many areas of applied economics, but has primarily been used to address weather forecasting information within the atmospheric community. Extending VOI to many sets of problems, particularly the seven Grand Challenges currently identified by the WCRP could be a good first step. Further developments in this area can highlight which of the many under-observed systems may have the most societal value.

To assess the economic value of a designed climate observing system requires understanding potential uses of climate information and how this may change or improve societal outcomes with changes in the climate information. The value of climate information lies in its potential to improve decision making. Measuring this requires comparing potential outcomes between a baseline (e.g., current and future climate observing systems without a "designed" observing system) and potential outcomes with improved information (i.e., a designed observing system).

VOI has demonstrated applications in areas from health, information science, energy, economics, agriculture, neuroscience, air quality, and land management (Garner & Thompson, 2012; Keisler et al., 2014; Lazo & Waldman, 2011). Economists have the necessary theories, methods, and applications for assessing potential changes in climate-related societal outcomes including potential reductions in health impacts and loss of life, mitigating impacts of sea level rise, improving agricultural practices, designing climate-appropriate energy systems, investments in water infrastructure. Much more work is needed though to understand how potential future changes in climate impact society and how decisions made today based on climate information may change outcomes in the future. For instance, decisions on development in certain coastal areas, planning for future water supplies, and efforts to make cities resilient to extreme events all rely on some estimate of the future climate. Imperfect information limits the certainty with which some of those plans can be made.

Figure 3 begins with consideration of a "business as usual" emissions scenario, which through climate sensitivity leads to an amount of global climate change and associated economic impacts over time. Meanwhile, scientists, the public, and government leaders are looking at climate change from past observations (center line in the figure). Scientists use these observations to determine uncertainties in climate model projections of past and future climate (IPCC, 2013). But both scientists and the public must look through three fuzzy lenses in interpretations of the past observations. The first fuzzy lens is that of natural variability of the climate system such as El Niño, Pacific Decadal Oscillations, solar variability, and volcanic eruptions. Most of this natural variability is caused by nonlinear interactions between the atmosphere and oceans that create "noise" in the climate system (e.g., El Niño). The noise of natural variability delays the time it takes to rigorously detect anthropogenic climate signals (Leroy et al., 2008; Weatherhead et al., 1998) and can confuse the public (e.g., the so called "hiatus" of warming from 1998 to 2013). The second fuzzy lens is the additional uncertainty in climate observations themselves. Most of the data systems used for long-term climate observations were in fact designed for other purposes such as weather, fisheries, air pollution, agriculture, land resources, or short-time scale scientific process research. As a result they often lack the instrument accuracy and sampling optimal for reducing uncertainty in decadal time scale climate observations. The third fuzzy lens is the uncertainty of climate model predictions for any given emissions scenario. In some cases, the climate models can be improved simply by improving computer power and therefore model space/time resolution to better resolve climate processes such as clouds. But typically, model improvement requires in

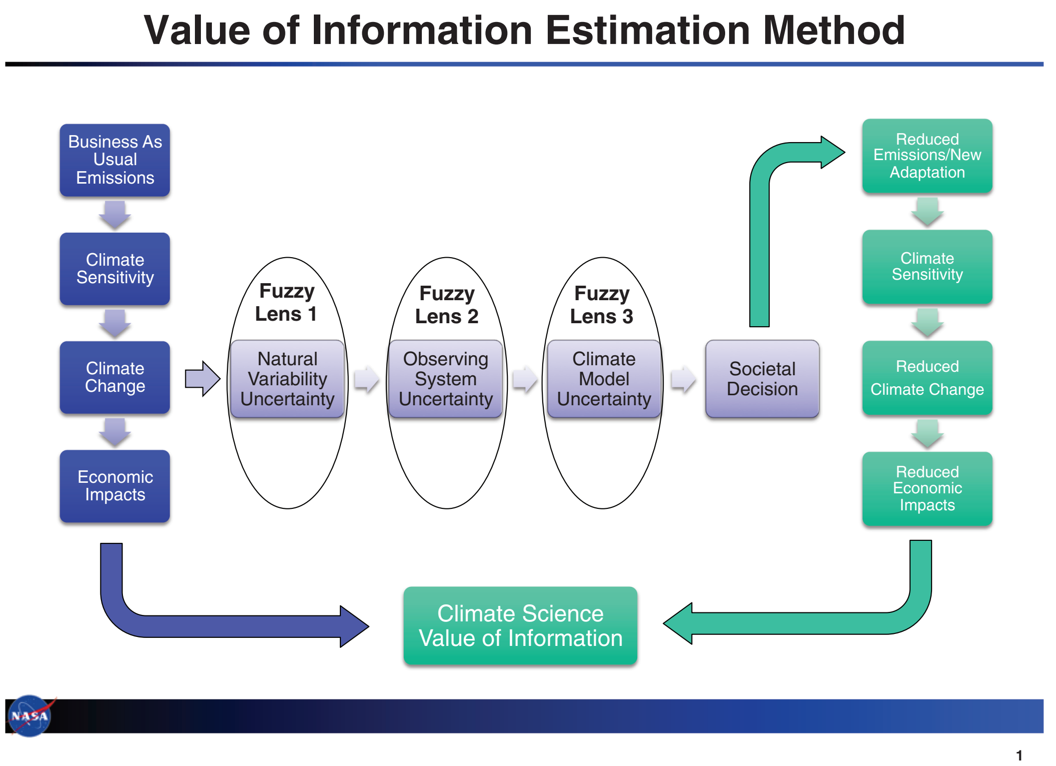

Figure 3. Business as Usual Emissions will directly affect climate and thus economic impacts. Imperfect knowledge of the climate system is partly due to natural variability, which can obscure underlying changes, and partly due to a suboptimal observing system, and partly due to needed improvements in climate prediction and projection models. With available information, decisions will be made that can result in societal actions. The value of information can be evaluated by economically evaluating the two scenarios.

addition improved climate process observations (e.g., aerosols, clouds, ice sheets, carbon cycle) as well as improved long-term monitoring observations required to test and validate their decadal time-scale projections by using past observations. Such observations can be in-situ or satellite based, but commonly require near global coverage to reach high confidence in conclusions.

As a result, the three fuzzy lenses shown in Figure 3 cause uncertainty in making effective societal decisions through under or over investment in mitigation (e.g., renewable energy) or infrastructure robustness in design. Once society decides to act, then progress can be made toward reduced emission scenarios, which lead to reduced climate change and reduced future economic impacts as shown on the right side of the figure. The difference between the amount of reduced economic impacts and the cost of mitigation can be used to evaluate the economic value of improved information such as an improved climate observing system. Such a higher accuracy system can “clear” the observing system fuzzy lens and can assist in clearing the climate modeling fuzzy lens. Better observations can provide clearer vision into the future.

While economics can help characterize the value of improved climate information, it should be noted that there is significant uncertainty about the future states of the world in which climate change will be actualized and thus it is extremely difficult to reliably quantify benefits far into an unknown future (unknown even without climate change). Such uncertainties may well be significantly greater than uncertainties in climate observations and modeling and thus make rational prioritization based on economic analysis difficult. In addition, in economic analysis future benefits need to be discounted back to present values, which is highly dependent on the choice of discount rates and functional forms for discounting (Nordhaus, 2007). Thus determining the VOI for designing climate observing systems involves complexities well beyond the physical sciences.

Planning the climate observing system to maximize societal benefits would require an understanding of what future climate-related impacts and benefits are and ways to characterize, measure, and compare potential outcomes. Because, to date, the climate observing system has not been planned, but has been pieced together from available observations, the current climate observing system has inefficiencies and, at times, ineffective observations. A more systematic evaluation of the observing systems would likely show that the investments are not currently commensurate with the importance and economic value of having a better understanding of future climate. Indeed, while the WCRP Grand Challenges were largely developed by the scientific community, driving and underlying these priorities should be societal preferences above and beyond current activities.

While a stronger investment may be justified given the current range of uncertainty in how the climate will behave, equally important is the economic question; whether the current resources are being spent appropriately to address the most pressing of climate questions. And even if the system is not optimized based on socioeconomic values, efforts should be made to evaluate net societal benefits to improve our understanding of potential outcomes. Using socioeconomic evaluations to demonstrate the importance of global climate observing systems will also help build support from policy makers and government and private sector decision makers. And while policy makers often require evidence of the net benefit to society from major investments, at a minimum, beginning to ask the question of societal benefits moves the community toward being able to prioritize investments in observing systems.

A summary and discussion of early research on the economic value of an improved climate observing system is provided in Appendix A.

5. Conclusion

Society now recognizes the role of climate science in managing water resources, planning infrastructure, and responding to severe events. Climate scientists, together with resource managers and policy makers, are ready to address the highest climate science priorities as summarized in WCRP's Grand Challenges (clouds, ice, extremes, sea-level, water, carbon cycle and near-term climate predictions) with coordinated scientific research supported by appropriate observations. We believe that these can be addressed by continued and improved observations and the associated analyses that will emerge from these observations.

Some initial steps that would help toward building the observing system outlined in this article above include: (1) identifying the most critical questions for each Grand Challenge, and the observations most suited to addressing these questions; (2) evaluating current observations with independent, quantitative analyses of their ability to address critical questions; and (3) establishing how best to augment existing observations to address these critical questions. When considering new observations, we need to think beyond existing and even proposed observing capabilities, with the explicit intention of fostering the development of varied new observing approaches.

Our biggest challenge in planning climate observations is to leverage what has already been done and work as a community to identify the key climate priorities. A climate OSSE approach, in some ways, reverses how new observations have been nurtured in the past, one where engineering capabilities often led the charge, then recruited science questions and scientists who can make use of those capabilities. The structure of this new approach engages the consumers of climate observations and works to identify priorities to significantly advance our climate observing system. This new paradigm for planning climate observations will support integrated, science-driven observations that underpin the highest priorities in climate science. The planned observing system together with the formal testing of proposed climate observations will result in large economic benefits to society and warrant additional investments in observations to serve society's most critical needs.

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Appendix A

Estimating the Economic Value of an Improved Climate Observing System

Building a designed climate observing system makes a great deal of sense from a scientific standpoint, but what about an economic perspective? Is such a system a wise economic investment? The purpose of this appendix is to summarize recent research on this topic.

A wide range of studies have examined the economic impacts and mitigation costs of climate change, including Working Groups II and III of the IPCC reports (IPCC, 2013). Much less attention, however, has been given to the economic value of improved scientific information on this societal challenge. Such studies are called "value of information" or VOI studies. For weather, the VOI is assessed by examining the value of improved accuracy in short term forecasts for hurricane tracks and strength, or warnings for frost, hail, tornado or severe storms. For long-term climate, value is related to narrowing the uncertainty of future predicted climate changes as a function of human emissions from fossil fuels. For example, the current uncertainty in ECS is a factor of 4 at 90% confidence interval (IPCC, 2013), a range of 1.5–6°C warming for a doubling of CO_2 in the atmosphere. To first order, there is a roughly quadratic relationship between the amount of global temperature increase and economic impacts (Interagency Memo on the Social Cost of Carbon 2010, hereafter SCC2010). As a result, a factor of 4 uncertainty in ECS leads to a factor of 16 uncertainty in long term economic impacts. These large impact uncertainties then lead to large uncertainties in the optimal investment strategy for early mitigation versus later adaptation.

Narrowing the uncertainty in ECS has been used in several VOI articles as an example of how improved scientific knowledge would lead to improved societal decisions and economic outcomes (Cooke et al., 2014, 2016; Hope, 2014). The Cooke et al. articles use a methodology shown schematically in Figure 3.

The climate change VOI estimates to date use one of the three Integrated Assessment Models (IAMs) used by SC2010 and the IPCC. These IAMs combine a simplified climate model tuned to the IPCC results with economic models of future economic development, costs of mitigation, and costs of adaptation. The three models are called DICE (Nordhaus, 1994, 2007), PAGE (Hope, 2006), and FUND (Anthoff & Tol, 2010; Tol, 2002).

The Hope (2014) article assumes that science can reduce the uncertainty in climate sensitivity by a factor of two, and then uses the PAGE IAM to estimate the economic value to global society of doing so. They derive an economic value of about $10 trillion US dollars in net present value using a discount rate of 3%.

The Cooke et al. articles use estimates of the accuracy of current observations, the potential improved accuracy of future observations, and the unavoidable noise of natural variability to estimate the time needed to detect anthropogenic climate trends using current or future improved observing systems. Recent studies have indicated that higher accuracy observations can shorten the time to detect trends by 15–30 years (NRC, 2015; Shea et al., 2016; Wielicki et al., 2013; Xu et al., 2017). Higher accuracy observations can then advance in time societal decisions once the observations reach the certainty level required by society. The value of this more rapid ability to made decisions is then shown to vary from $10 trillion to $20 trillion US dollars depending on the climate variable. The Cooke et al. results also use a net present value metric at 3% discount rate. The analysis performs a Monte Carlo analysis over the full range of ECS uncertainty in IPCC (2013) report and the final VOI is the expected value over the entire ECS distribution. Cooke et al. (2014) note that while the example calculation uses uncertainty in trends in one climate variable, societal decisions will clearly depend on the results of confirmation from a wide range of climate variables, so that their results should be considered as the value of an improved total climate observing system and not just one component of such a system. In that sense the VOI is the value of reaching a given level of uncertainty in climate change observations 15–20 years earlier than with less capable observing approaches.

Net present value or NPV is a standard economic accounting metric that enables a more direct comparison of the value of investments made today with the payback of those investments in the future. The annual discount rate is the concept that allows that comparison. The discount rate is applied for every year into the future the investment will provide its return. An investment that returns in 20 years will be discounted or reduced by 1.0320 or a factor of 1.8. A return in 50 years will be discounted by 1.0350 or a factor of 4.4. The correct discount rate to use remains an issue of research in the economics community and can vary from 1.5% to 5%, with 3% as a common value (SCC2010). A discount rate of 5% would lower the VOI by a factor of 4, while a discount rate of 2.5% increases the VOI by a factor of 2 (Cooke et al., 2014). From an investor (public or private) point of view, discounting is the sum of a risk free rate and compensation for investment risk. Climate sensitivity is large (i.e., uncertainty on risk is high), despite climate change being close to unequivocal, i.e., risk is high). For the same discount rate, investment will go to the lower ultimate risk. For a same ultimate risk, the investment will go to the higher discount rate.

The first question often asked about these studies is how the economic value could be as large as trillions of dollars. A simple scaling argument helps understand the results. The world Gross Domestic Product (GDP) is currently about $80 trillion US dollars per year. Climate change impacts in the second half of the 21st century are estimated to reach between 0.5% and 5% of global GDP ($0.4–$4 trillion US dollars annually) depending on climate sensitivity and societal decisions (SCC2010). As a result, the impacts could range from a level less than that of the recent financial crisis in 2008 to a level much larger than that crisis, but extending over many decades instead of several years. Even modest optimization of that economic risk leads to large economic value, value that is measured in trillions, not billions.

The second question often asked is about the robustness of the results. There are two key aspects of this question: (1) uncertainty in the economic costs of future climate impacts, and (2) sensitivity of the results to timing and methods of societal decisions which are very uncertain. Estimates of climate impact costs vary in the current IAMs by a factor of 3 (Kopp et al., 2012). In addition, there are many climate impacts that have not yet been incorporated in the estimates. These include the impacts of ocean acidification, species loss, or any international conflicts caused by the stresses of climate change on populations and economies. The Cooke et al. (2014) article estimated the impact of unknown societal decision points or "triggers." This was done by varying the magnitude of climate trends required for a decision trigger (e.g., 0.2°C or 0.3°C per decade warming), or varying the statistical confidence of the observed anthropogenic climate trend (95% versus 97.5% confidence interval). The sensitivity of the VOI to these assumptions was about 30%, much less than the discount rate or damage function uncertainty (Cooke et al., 2014). The reason for the robustness to the specific societal decision trigger was found to be that the VOI was a differential measure: no matter what information society required, it would ultimately be provided 15–20 years earlier by a more accurate observing system.

While the economic value of a more accurate and complete climate observing system is clearly large, understanding its return in investment requires estimating the cost of such an observing system. Cooke et al. (2014) estimated that a tripling of the current global climate research from $5 billion to $15 billion US dollars per year might be needed for at least 30 years. The additional $10B per year global cost of such a system in net present value is ~$200–$250 billion US dollars. When compared to a $10–$20 trillion VOI, the return on investment varies from 40 to 100 to 1, or roughly $50 return for every $1 invested. Because of the long time scales involved, most of that return occurs several decades after development of the more advanced climate observing system. Cooke et al. (2014) also investigated the cost of delaying such an advanced climate observing system and concluded that the world would lose roughly $250 billion per year of delay (NPV, 3% discount rate).

Early analysis of the economic value of an designed more accurate and complete climate observing system suggests an economic value of $10–$20 billion US dollars, a 50 to 1 return on investment, and a $250 billion loss for every year of delay. Even if total uncertainties in the economic analysis were a factor of 5 below or 5 above such estimates, the return on investment would range from 10:1 to 250:1, a wise investment in any event.

Future directions of climate VOI research are examining the effect of combining multiple climate variables in the societal decision trigger using Bayesian Net multivariate statistical approaches. Further steps might extend the analysis to narrowing uncertainty in additional climate variables such as aerosol radiative forcing, sea level rise, or carbon cycle feedbacks.

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