Designing the Climate Observing Systems of the Future

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1.0 The Challenge

Climate change is well understood to be one of the major risks to modern society as well as one of the greatest science challenges of this century (IPCC, 2013, USGCRP, 2014). Yet we lack an observing system specifically designed to address this joint societal/scientific challenge of climate change (NRC, 2007; Trenberth et al., 2013; Dowell et al. 2013). While we have a wide range of Earth observations from surface to space, very few have been designed to climate change requirements. No international agreements or commitments exist for designing, building, and maintaining a climate observing system. A well designed suite of climate observations made over several decades have the potential, in conjunction with appropriate models, to characterize key processes, to resolve outstanding climate questions, and to quantify the uncertainty range on climate sensitivity. These observations will also be crucial in leading to the ability to do climate predictions that can better serve society.

Climate change presents major challenges for society. The approaches to addressing it are labeled "mitigation" which refers to decreasing emissions of heat-trapping greenhouse gases such as carbon dioxide as well as stopping and even reversing deforestation, and "adaptation" which refers to planning for the consequences, but the key issue then is what should be planned for? This is where a third approach is essential, one of building a climate information system that provides information on what is happening and why, and what the prospects are. A core component of the much needed climate information system is a climate observing system. Indeed the economic risks for climate change are measured in Trillions of dollars. Given this challenge, can the USGCRP put forth a vision of how such a system might be designed and built? How its economic value to society might be estimated?

First, it is worth emphasizing that in addition to climate quality observations, the "system" aspects need to be emphasized. What is needed is an end-to-end system that extends from continuous climate quality observations, their quality control, processing and analysis into global and regional maps and products, and transforming those products into useful information applicable to many sectors of society and disseminating it in the form of climate services. This may be considered the core observing system. But in addition the observation products set the stage for initialization and testing of climate models to enable predictions and projections of what happens next on various time scales, as well as attribution studies to determine what is happening and why. These activities feed back into the observing system to make demands on the observations made and how they are processed. Together these activities and the climate services provide a comprehensive climate information system.

Recent research studies (Cooke et al. 2014, 2015) 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). In the simplest sense, this is the economic value of moving climate science learning forward by 15 years using better observations, analysis, and modeling/predictions. The study 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 could 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. We need to change the question from "which critical science climate observation is more important?" to instead "what climate science observations are of high value and return as a societal investment?"

Design of such an advanced and more rigorous international climate observing system would be a challenge in itself. Key elements of such a design might include:

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, algorithm uncertainties.*

Defining the science goals or questions is an area where USGCRP can greatly assist in focusing the many under-observed areas of climate science. A good starting point for general categories of needed research is the World Climate Research Program which has worked across disciplines to identify five Grand Challenges. Once science goals are identified, the challenge is to link their solution to more rapid progress in climate change assessment, attribution, prediction and understanding and thereby economic value through enabling improved societal decisions. This is the type of step well suited to the USGCRP or NRC study of processes and can build on priorities previously identified by the USGCRP.

OSEs utilize a data assimilation system that is run with and without a particular set of observations to assess their impact, possible biases, and other issues, and are routinely performed when new observations come on line (especially from a new satellite). Climate OSSEs can identify the usefulness of the different measurements needed to achieve the science goal or question, with specific input to the elements in the list above. For weather prediction goals this is accomplished through weather OSEs and OSSEs (Atlas 1997, Atlas et al 2015a,b) and for ocean OSSEs (Halliwell et al 2014 and Oke et al 2015), while for climate change we propose that Climate OSSEs or COSSEs are the relevant tools. This is an area that still needs substantial development in the climate research community and can improve the soundness of investments in future observations. Climate OSSEs 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. As the variety of science questions is broad, so are the types of approaches to evaluate proposed observations.

A great deal of work has already been done on the "Essential Climate Variables" (ECVs) needed for a climate observing system through the Global Climate Observing System (GCOS), with the latest assessment and recommendations just released in October 2015 (GCOS 2015). The ECVs have been developed in a fairly pragmatic way that takes 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 needs for reprocessing and reanalysis of variables to produce consistent homogeneous datasets (see also Trenberth et al. 2013).

The design elements in the list above are similar to the recent NRC Continuity report (NRC, 2015) concerning prioritization of continuity for satellite observations, including those for climate change observations. These design elements have also been addressed individually by proponents of specific observing systems. A formal COSSE effort would allow for critical comparison of different systems based on similar criteria and incorporating realistic variability albeit with assumptions related to the veracity of the model used.

The difficulty of achieving this objective should not be underestimated. One of the key challenges is coordination across disparate research communities with only modest or minimal overlap. These communities include surface and in-situ based climate observations, satellite based climate observations, climate modeling and projection science, economics of climate change impacts, and climate policy. In the U.S., the U.S. Global Change Research Program (USGCRP) is currently the only major organization charged with such a broad charter. Internationally, the World Climate Research Program is another such organization. GCOS is a system of systems with a more narrow focus, but it works with WCRP to further the goals. Ultimately a vision is required that can be effective at both national and international levels. The challenge is made more difficult by the fact that neither the USGCRP nor WCRP and GCOS control any significant budgetary resources, so that their influence must arise from production of a clear vision of the large value to society of such a climate observing system that can be broadly supported by scientific leadership, and implemented by national and international efforts.

This view suggests that future observing systems to support climate change research need to be organized and evaluated around clear, testable hypotheses with quantifiable performance measures. Current and future observing systems should be categorized according to how they serve particular quantified climate goals. We expect such goals to be closely aligned with the USGCRP research goals, WCRP Grand Challenges, and IPCC major uncertainties in the Working Group I reports.

Once scientific requirements and recommendations are made, additional considerations will likely be undertaken by individual agencies in making specific choices. These considerations include both costs, timeliness of execution and likelihood of success (NRC, 2015).

After a new observing system is employed, additional work will be needed to:

1. *Develop and improve analysis and processing methods to produce timely products for multiple uses (some of which might be transitioned to the private sector).*
2. *Develop initialization of climate models and carry out predictions on multiple time scales.*
3. *Analysis to improve climate processes and their representation in climate prediction, projection, and Earth System models.*
4. *Continue to develop climate services to disseminate information and receive feedback on user needs.*
5. *Carry out comprehensive evaluations of the observing system and make recommendations on how to improve it and cut costs. A key part of this activity involves use of Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) involving models.*

The current white paper focuses on two key aspects of the above observing system design elements: quantified science objectives and Climate Observing System Simulation Experiments (COSSEs). COSSE tools would provide a key 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. 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 the LHC. For climate change, climate models replace the Standard Model for hypothesis development and testing. Some of the discussion presented here is broader than COSSEs, but is provided in order to put the COSSE discussion in the context of the larger societal and climate science goals.

2.0 Background: Current Climate Observing Systems

Monitoring the Earth system is a key responsibility of national agencies and is coordinated through international bodies such as GCOS and CGMS (the Coordination Group for Meteorological Satellites). 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. However, disruptions in observing systems and the use of systems not designed for climate change observations have resulted in increased uncertainties in climate records and increased uncertainty in key climate change science such as measurement of aerosol radiative forcing, or measurement of cloud feedback to constrain climate sensitivity. 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 future climate change are large; and progress in advancing our understanding is, in many cases, limited by the observations available. For example, the 90% confidence in climate sensitivity (amount of warming for a given CO2 level) remains a factor of 4, while the ultimate economic impacts scale as the square of the amount of warming: or in the long term roughly a factor of 16 (IWG-SCC, 2010).

Past and existing climate observing systems have often been focused on single observing systems and, in many cases, have been driven by engineering developments. Further, these systems have often been designed for other purposes such as weather prediction, land resource management, agriculture, air pollution, or other operational and research topics, most of which are sub-optimal for climate observations. Individual efforts to assess the value of added observing systems have often been advanced in an ad hoc manner, focusing on one aspect of the Earth System. The results have advanced understanding 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 systems are incredibly valuable and cost effective, they are far below the capabilities that even existing measurement technologies could achieve if applied to an advanced climate observing system. Limits today are primarily economic and not technological. It is in this sense that an improved climate observing system is primarily a discussion of investment value for society. Urgency is needed as observation delays are especially problematic given the long time scales of both climate change and societal policy actions. The economic value study mentioned earlier estimated a $650B per year cost to society for every year we delay an advanced climate observing system. At the same time, we must have a way to prioritize and estimate cost/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", while hoping for a miracle break through. This 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 (2013). Even more problematic, it remains unclear that the next 35 years of our current observations will solve this key challenge (Wielicki et al. 2013, Trenberth et al. 2013).

This paper proposes a re-examination of what is required in a climate observing system as an effective societal investment. The long term goal is for such a discussion to lead toward development of an international climate observing system analogous to the current international weather observing system; a rigorously designed system with international commitments to provide key observing system components, whether surface, in-situ, or space based.

3.0 An Improved Approach

The climate observing system of the future will need to support three types of goals: monitoring the Earth, advancing models of climate processes and improving climate projections. Each of these areas is expected to drive quantified science hypotheses and goals, and would in most cases be relevant for COSSEs to better understand requirements.

3.1 Quantified Science Hypotheses, Goals, or Questions

These overarching goals will then lead to a list of key quantified science questions. Such a list will evolve over time, as knowledge about the climate system evolves (e.g., what are the key uncertainties?), as understanding of observing system strengths and weaknesses evolves (e.g., what accuracy was achieved vs planned), as knowledge of climate prediction strengths, weaknesses and uncertainties evolve, and as measurement technology capabilities and costs evolve.

For critical climate science questions, some groups have already organized thoughts and identified priorities for climate research. Key among these has been the IPCC WG I report (2013), the World Climate Research Program (WCRP) identification of Grand Challenges: Clouds, Circulation & Climate

Sensitivity; Melting Ice & Global Consequences; Climate Extremes; Regional Sea-level Change & Coastal Impacts; and Water Availability, as well as GCOS and COSPAR. Further progress may be obtained through the USGCRP or through the new NASA/NOAA/USGS NRC Decadal Survey. A shortcoming of many of these efforts to date, however, is that goals are often expressed as qualitative understanding as opposed to quantitative hypothesis testing.

There are four other existing climate observation assessments that should be mentioned in the context of defining and prioritizing climate observations and their goals.

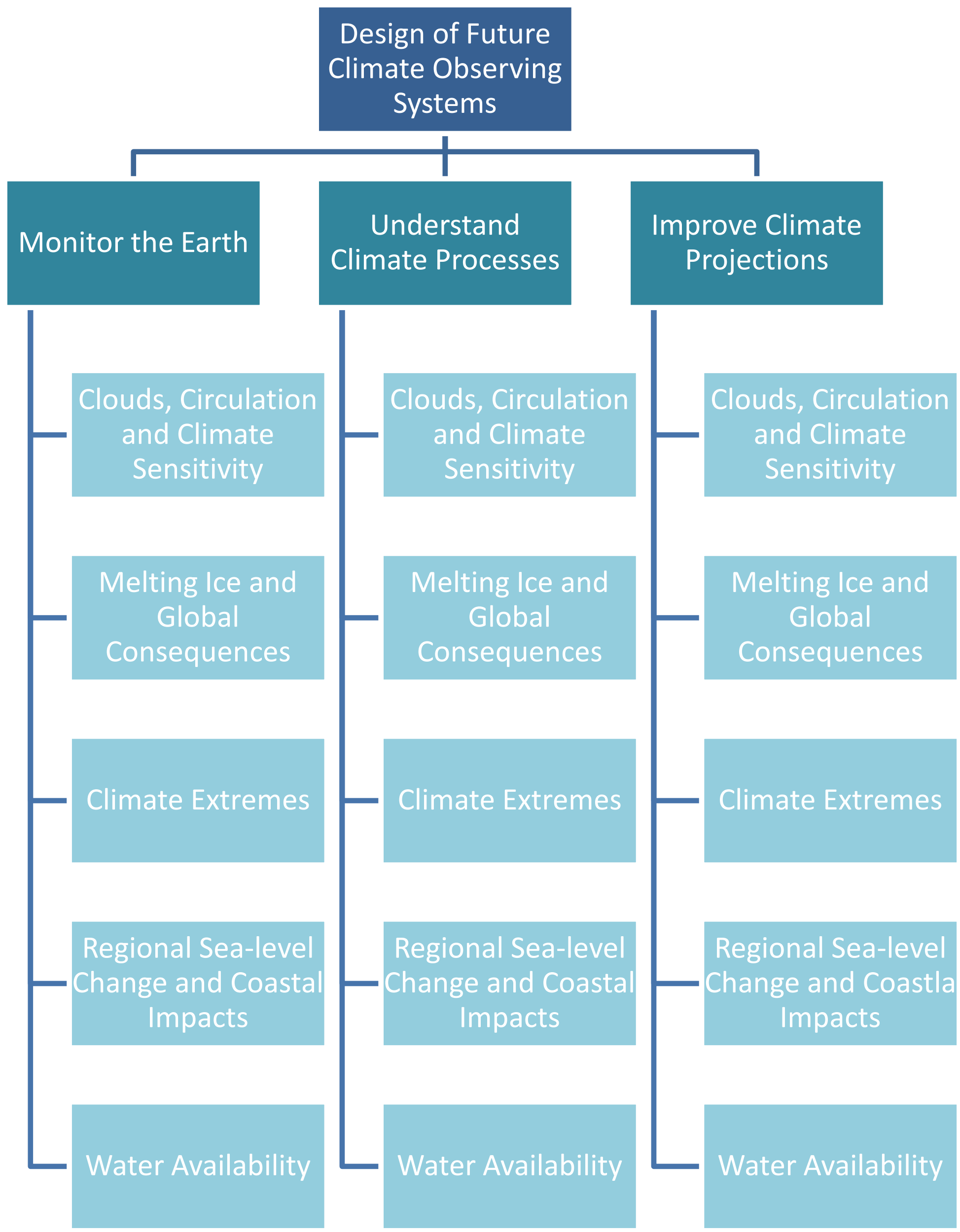
First, the second U.S. Earth Observation Assessment (EOA-II) is underway. Unfortunately EOA-II does not prioritize using economic benefit across its 13 Societal Benefit Areas (SBAs), so that climate change becomes by definition 1/13th of the nation's priority for Earth observations. In addition, priorities are based on qualitative evaluation of key objectives and not on quantified goals. Even more problematic is that only current observing systems are being considered for importance to current products, services, and outcomes. This means that EOA-II cannot evaluate the increased value to society of an improved climate observing system (or any other earth observing system).

Second, NOAA has recently carried out a NOAA Observing System Integrated Analysis (NOSIA-II). This analysis is somewhat similar to the EOA-II approach of assigning priorities to existing services and products with a subjective evaluation of their impact or value (example: a qualitative Priority 1 through 5. NOSIA-II does use some OSSE information for weather in a very limited way, but does not for climate change observations.

Third, the WMO/WCRP/GCOS (Global Climate Observing System) documents are a very good survey of current and planned observations, 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 (2010) also defines ~ 50 essential climate variables. Again, these variables have not been defined using COSSEs, but are subjective selections based on current observation capabilities combined with climate science experience and intuition.

Fourth, the Committee on Space Research (COSPAR) of the International Council of Science has prepared a new assessment and recommendations: "Observation and Integrated Earth-system Science: A roadmap for 2016-2025". Its focus is 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.

We conclude that no existing or near term studies are designed to define the required climate observing system with its economic value to society. We hope the WCRP, USGCRP, or NRC will step forward to define quantified climate science objectives as the key starting point of defining an advanced climate observing system. Once quantified objectives are decided, the next step is to quantify observing system capabilities using COSSEs.



Caption: Proposed organizational structure to catalogue 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; by campaign versus long-term monitoring; or by platforms (satellite, *in situ* and ground based). This organization should help decision makers, researchers and instrument developers understand what observations are available, being planned, needed or up for evaluation. 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. Currently, two additional Grand Challenges are under consideration: seasonal/decadal forecasting and carbon cycle.

It would be useful to recognize the weather events in the context of a climate change context, be it heat waves, droughts, floods, Arctic summer sea-ice extent and thickness etc. 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 Observing Systems (as well as the associated Modeling) will need to expand on this point.

3.2 Examples of Climate Change Quantified Testable Hypotheses and Goals

Below we give a few examples of potential quantified hypothesis or goals.

Hypothesis: The expansion of the tropics is occurring and is directly related to climate change driving 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 degrees K), humidity (+/- 2% RH) and wind (+/- 2m/s) every 100 meters from the surface to the mid-stratosphere over the tropics (30N to 30S) for three decades. Horizontal sampling and accuracy requirements TBD using COSSE.

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. Example observational requirements: Observations every three days of stratospheric ozone levels (+/- 2%) across all latitudes (90N to 90S) for a minimum of ten years. Sampling and accuracy requirements to TBD using COSSE.

Hypothesis: Solar activity influences climate. In order to monitor such changes in solar radiative forcing, determine Total Solar Irradiance to an SI traceable absolute accuracy of 100ppm and stability of 10ppm/yr (NRC TSI report, 2013). Determine Spectral Solar Irradiance to an absolute accuracy of 4% and stability of 0.75% /yr. TSI and SSI observations sufficient to determine monthly averages at the SI 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 (+/- 2m/s) at N different locations for a period of four years. Space and time sampling, vertical resolution, and accuracy TBD using COSSE.

Hypothesis: Upper tropospheric temperatures are increasing at approximately 0.2 degrees K/ decade. Monitor this trend with an uncertainty of .08 K/decade (95% confidence). Observational requirements:

continuous measurements of temperature (+/- 0.1 degrees K), from the boundary layer to the lower stratosphere, every 10 mb, (60N to 60S) continuously. Accuracy, vertical resolution, spatial resolution and time resolution determined using COSSE.

Hypothesis: Regional fluxes of carbon from the Eastern half of CONUS is within 15% of the global carbon flux estimates on an annual basis. Observational requirements: 3000 flask measurements per year across the Eastern US for a period of three year. Number of flasks determined by initial COSSE effort.

Goal: Determine the change in global ocean heat storage over a decade time scale to within 0.1 Wm^{-2} and over annual time scale to 0.2 Wm^{-2}. Requires 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, global net radiative flux. Observations required for at least 50 years. Accuracy of 0.1 W/m**2, space and time sampling requirements TBD using COSSE. VonSchuckmann et al., 2015

Goal: Narrow uncertainty in equilibrium or transient climate sensitivity by a factor of 2 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 CONCEPT HEAT within CLIVAR, and observational requirements TBD using COSSE.

Goal: The rate of sea level rise from ice sheet loss is likely to be nonlinear and to accelerate in a warming Earth. Determine the rate of sea level rise to a global mean accuracy of 0.2 mm/yr. Observations required indefinitely. Observation requirements beyond current ARGO, and GRACE measurements (sea level rise, ice sheet mass, ocean temperature and salinity profiles (thermal expansion), mountain glacier mass loss) determined using COSSEs.

Goal: Observe or estimates solar radiation at a 1 km2 resolution across the CONUS to an accuracy of 5% over a one hour period. Required to support renewable energy applications. Accuracy, time sampling, space sampling requirements TBD using COSSE. Importance based on analysis of economic value of improved capabilities.

Goal: Measure or estimate boundary layer winds, turbulence, vertical sheer and boundary layer height. 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 TBD using COSSE. Importance based on analysis of economic value of improved capabilities.

While these are not 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 hypothesis with quantifiable observational requirements, it is possible that new technologies may be developed that will allow for cost-saving, innovative approaches to observational needs. Side benefits of observations, such as their potential usefulness to disaster response or weather forecasting may also be identified.

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 vs 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 change to societal decisions and economic impacts, such verification is a key characteristic of a future rigorous and robust climate observing system. A similar independent verification is used for the climate sensitivity example.

All quantified hypothesis tests or goals will not be equally important. In principle an infinite number of such tests and goals could be constructed. "All climate science children are equal" would not be a useful metric in this case. Instead, the importance of these tests/goals to understanding and predicting future climate change, including their societal impact could be used to prioritize the hypothesis tests or goals. For example, an importance 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.

3.3 Key Results from the National Academies' Continuity Report.

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," here referred to as the Continuity Report. 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 overlap with the goals of this climate OSSE document. Specifically, the focus of planning from the Continuity Report is on assuring that key science questions are addressed and that proposed systems are evaluated with respect to their ability to address these key science questions.

The Continuity Report identifies societal benefit as the key motivation for collecting observations, with four key aspects of benefit defined as: importance, utility, quality and success probability:

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).

In addition to these four key aspects, affordability is added as an additional discriminator in evaluating proposed observing systems.

The report highlights specific recommendations for assuring appropriate planning of future observations, including the recommendation to foster a consistent methodology to evaluate the utility of geophysical variables for achieving quantified Earth science objectives, with specific recommendations that this be utilized by the Earth science decadal survey.

The priorities listed in this report are in direct agreement with the principles listed in the Continuity Report. This report expands and gets specific on proposed areas of scientific importance with the identification of the World Climate Research Program's Grand Challenges, and offers a path forward for evaluating both quality and success of proposed observing systems.

3.4 Climate Observing System Simulation Experiments (COSSEs)

The Continuity Report highlighted that 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. The Continuity Report further highlighted that a common approach for evaluating systems does not currently exist. COSSEs allow observing system requirements to be directly related to physical hypothesis testing using climate models. They can be used to address the three major climate observing system elements: *climate change 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 efforts have already begun to develop COSSEs for aspects of climate observations including ocean heat content (Argo), carbon cycle sources and sinks (OCO2 and CarbonTracker), temperature trends using radio occultation (COSMIC) and cloud feedbacks (CLARREO/CERES). Most of these COSSEs have focused on decadal change measurements, but some involve climate processes (OCO2, CALIPSO). COSSEs can be used to evaluate many aspects of climate observations, ranging from instrument accuracy requirements (CLARREO) to estimations of retrieval uncertainty (OCO2) and/or sampling uncertainty (CALIPSO, OCO2, COSMIC, CLARREO). Quantification of such requirements is key to evaluation of cost versus benefit for a climate observation. But many climate observations have yet to develop COSSE capabilities. 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 COSSE to continue the development of the science to support strong COSSE results.

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 isolate the observational capabilities as appropriate.

When applied to improving climate process observations (e.g. aerosols, clouds, chemistry), it is often required to run very high resolution process models as COSSEs which would be too computationally expensive to run in a 100 year climate change simulation. In these cases, model resolution might change from the ~ 100 km resolution of an IPCC 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 pollution 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 3km resolution simulations) might be very useful for climate process COSSEs. Similar advances in air pollution prediction OSSEs could also be 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 (LES) models run at 10s of meter grid scale, or deep convective Cloud Resolving Models (CRMs) run at ~ 1km grid scale.

While current 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 be used to 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 "Quantifying Uncertainty in Complex Models" (NRC, 2012). This report also summarizes the limitations of using Bayesian approaches. Where applicable, the Bayesian approach should be a long term goal of more rigorous understanding of climate observing system requirements. The major challenge of a PPE Bayesian approach to COSSEs is the increased human and computer resources required to process, store, and analyze a large number of COSSE simulations. Developing techniques to address the seasonal, daily and sub-hourly variability will require scientific investment that will likely lead to new insights about the requirements for climate observations.

One major advantage of COSSEs is that by their very 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 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. Often a new observation technology can be a hammer looking for a nail. Alternatively, 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 development and use of new technologies.

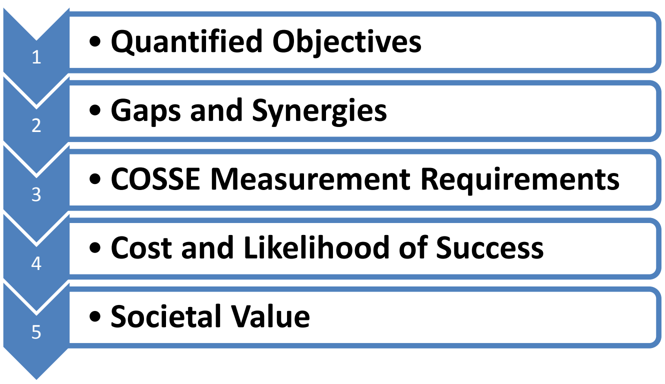
As described above, COSSEs provide a link between climate hypothesis tests/goals and modeling in related disciplines such as weather and air quality. This is often expressed as “seamless prediction” from weather to seasonal to decadal earth system prediction. In the same vein, we recognize that climate models for Earth's climate system are often modified to be tested for their ability to handle a much more extreme set of planetary atmospheres such as Venus, Mars, Titon or Pluto. 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.

4.0 Activities and Organizational Structure

Designing an observing system to meet the climate science goals requires thoughtful engagement of the community, building from existing efforts and respecting current organizational structures. Carefully designed activities can help change the paradigm for planning 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 propose a number of activities that can help achieve this goal.

4.1 Societal Context for Designing a Climate Observing System

The activities required would be closely related to the key design elements mentioned in section 1.0, namely quantified climate science objectives, utility of each measurement to achieving the objective, quality of the measurement required, and finally the cost and success probability of varying approaches to making the measurement. Proposed activities are given below.



Caption: The activities to support a climate observing system which supports the goals of monitoring the Earth, advances climate processes and improves climate projections can result in a robust observing system that serves science and society in a cost effective, fully justifiable manner.

There is a need to further articulate the economic costs/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 the work needs to be done to unambiguously address damages to life and property on time scales from storms, to inter-annual climate changes to longer timescale trends. Work needs to build from and expand beyond the economic evaluation of weather related disasters (e.g., hurricanes, tornadoes). There needs to be a linkage whose quantification becomes acceptable to a large community. Well-accepted quantifications and analyses need to be addressed by both climate scientists and economists starting with existing techniques and, where necessary, developing new techniques. Examination of past events on timescales longer than daily and weekly events may be a starting point; or alternative economic techniques may need to be evaluated. A quantified answer based on some 'case studies' from the past, over a period during which the observed changes are robust, would help communicate the benefits of a coherent observing system strategy.

In looking to assessing the economic value of future information, the branch 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 five grand challenges currently identified by WCRP could be an important starting point. VOI has been applied successfully in neuroscience, weather forecasting, and land management; the extension to climate information is a likely area for high success; further developments in this area can highlight which of the many under-observed systems may have the most societal value.

4.2 Activities

Activities to support outlined COSSE work can be identified as follows:

Activity 1 Quantified Objectives

Challenge the community and engage subject matter experts to create a set of quantified hypotheses/goals for the most important challenges, and to prioritize them. This should be achieved through focused discussions, both in person and via remote access discussions, involving agency and academic subject matter experts. The focus in all discussions should be on what outstanding climate issues are of highest importance and could be significantly addressed with better observations. Testable hypotheses with quantified observational requirements should be strongly encouraged at this phase. Similar to NASAs use of NRC decadal survey reports, the priorities need to be set by the climate science community as opposed to the developers of particular observing systems. This activity could be carried out by the USGCRP or by activities such as the NRC Decadal Survey or by an NRC study specific to this activity.

Ultimately these quantified hypotheses and goals will need to be vetted in the international research community as well. While international agreement on goals and priorities is ideal, it is not required. Given the need for independent verification of observations and analysis (similar to nuclear physics or metrology research communities) there may evolve one U.S. climate observing system and separate international observing systems, thereby supporting independence of observation and analysis. These hypotheses and goals will need to cover all three key aspects of climate science: climate monitoring, climate process studies, and climate prediction. The list of these quantified objectives can be maintained on the USGCRP web site, including their priority.

In determining requirements, there will be a natural tension between the priority of an objective, its measurement requirements, and current observational capabilities. Five different situations are likely to occur.

- *Requirements are understood and are consistent with current observational capabilities.* Technology and costs are well understood (e.g. monitoring TSI). This category is consistent with a requirement for continuity of existing observations.

- *Requirements are understood, they require an advance in current observational capabilities and the technologies to provide such advances have been demonstrated*.
  Examples might include spaceborne gravity ice sheet mass observations (GRACE), Reference Radiosondes, deeper ARGO float vertical profiles, lidar to advance accuracy of cloud height and amount trends, or CLARREO spectrometers to provide reference calibration to the Global Space Based Intercalibration System (GSICS) for more accurate reflected solar and infrared space borne instrument calibration over decade time scales. In these cases there is a need to evaluate the impact and value of the observing system improvement relative to its cost. This category is consistent with a wide range of potential advances in climate observations that are not yet part of a designed and committed climate observing system.

- *Requirements are understood, they require an advance in current observational capabilities, technologies have been demonstrated that may or may not be able to meet the requirements*.
  In this case further demonstration of new technologies is required before commitment to long term observations as part of the climate observing system. The urgency and value of such demonstrations should depend on the priority of the quantified climate science objective. Examples include the 2007 Decadal Survey ACE mission for improved observations of aerosol radiative forcing, or the ASCENDS mission for improved observations of carbon dioxide source and sinks. This category is consistent with the need to develop and demonstrate improved observation capabilities. Once demonstrated, such capabilities are then considered for inclusion as part of the climate observing system.

- *Requirements are understood but no current technologies are available to meet the requirements*.
  This category of observations requires long term technology development programs. The NASA ESTO program is an example. In the case where partial fulfillment of requirements can be met with current technologies, the priority of the current observation technology can be evaluated as discussed in the 2015 NRC Continuity report. For high priority objectives it is likely that partial fulfillment of requirements will still be of high value but will need to be augmented by technology development programs.

- *Requirements are poorly understood*.
  In this case, further investment in exploratory research is required. Such research should include advancing modeling capability along with COSSE capability. Technology programs are also relevant to success in such areas. Ice sheet dynamic modeling is an example of a rapidly evolving capability and improved understanding of climate change requirements. Another such area is surface hydrology. This category of observations may be able to

demonstrate a high societal value (e.g. sea level rise and drought) without as clear an understanding the observational requirements required. Research support is required for such areas to evolve into better understood requirements, observations, and technologies. A significant portion of the climate observing system resources will need to be dedicated to such efforts. Not all climate observations are ready for quantified science objectives and COSSE quantification of requirements. Nevertheless, research in these areas should include efforts to move toward more quantified objectives and COSSE capabilities.

Activity 2 Compare the Quantified Objectives to Existing Observations and Plans for an Initial Evaluation of Gaps and Synergies

Once the quantified hypotheses and goals are established and prioritized, gather the current agency priorities, reports and literature, covering both space-based, *in situ* and land based technologies and identify critical gaps and synergies.

This information should be gathered into a public and easily accessible website with the opportunity for additional input and comments. A potential organization for the existing information might be the same organization for the five Grand Challenges identified by WCRP. Part of this activity will be to identify current and planned observing systems and, to the best of current ability, evaluate their value to identified climate observing priorities. Observing systems will include public, private and academic sectors which have or will have significant national or global impact. This activity may include a brief evaluation of relevant international efforts that offer opportunity or guidance to the planning of the US observing system. This effort will need to be updated every 3 years with a report to the USGCRP.

Identify synergies for all proposed observing systems as they apply to the climate goals. For example, a proposed weather observing system will be evaluated for its potential value to the testable climate hypothesis either as a critical or supportive observing system. This examination may help to modify the characteristics of the proposed system. Similarly, observing systems designed to address, as an example, atmospheric circulation changes (WCRP Grand Challenge #1), may also be of value to questions of regional sea level changes and coastal impacts (WCRP Grand Challenge #4). The approach is similar to NOAA's NOSIA-III effort to understand the value of observing systems across a diverse set of applications. Note that until COSSE capabilities are further developed (Activity 3), some of the measurement requirements during this activity will not be well understood. The rigor of these requirements will, however, improve as COSSE capability improves.

Activity 3 Use of COSSEs to Define Measurement Utility and Requirements

Use the information in Activities 1 and 2 to define Climate Observing System Simulation Experiments (COSSEs) needed for the proposed observation system. Note that COSSEs are relevant both for defining the utility of the measurement for a given quantified science objective as well as to define the measurement uncertainty requirements (accuracy, stability, spatial extent, resolution and sampling, temporal resolution and extent, algorithm uncertainty and confounding factors that can impair measurements). Weatherhead et al. (1998 and 2002) proposed tools that are currently adopted to estimate the effectiveness of systems to detect trends. These approaches have been successfully applied to virtually all important climate parameters including temperature, water vapor, ozone and winds. The current COSSE proposal offers to expand these efforts to estimate effectiveness of advancing climate processes and improving climate projections.

It should be noted that most well-funded, proposed observing systems have some estimates of how valuable that observing system will be to climate science. A current challenge is that these efforts are generally funded and/or carried out by research groups proposing the new observing system. The result is sometimes overly optimistic assessments of an observing system's value. Even when these results are published in the peer reviewed literature, there may not be independent analysis of the observations value carried out. The current *ad hoc* climate OSSE efforts are each carried out independently; the results are often difficult if not impossible to compare for relevant value of different observing approaches. The weather OSSE approach (Atlas et al., 2015a) illustrates how an independent assessment of proposed observing systems can offer unbiased estimates of observing capabilities for proposed systems. These challenges suggest that independent peer reviewed COSSEs be carried out for proposed observations. These might be a combination of both centralized COSSE capabilities as well as distributed competitive COSSE efforts. The key to open and objective results is peer review of both proposals and published COSSE results.

A COSSE will attempt to estimate future observing measurements under realistic assumptions about weather, climate, and instrumentation characteristics. The COSSE will take into account the other available observations that may be critical to ensure stability or add value to the considered observing system. For example, GPS occultation observations will be evaluated with an understanding for what water vapor, pressure and temperature will be available. COSSE studies may include surface, *in-situ* and space based measurements. Where appropriate, the current weather OSSE effort will be used to help simulate actual atmospheric conditions.

COSSE efforts will drive early interaction between data providers (a new instrument or sampling capability) and data users (modeling groups) to better understand the measurement capability, its use in testing and improving models, and the trade space of measurement requirements. Such early interactions would also lead to more rapid use of measurement data once it becomes available. Such interactions would move beyond the common "build it and they will come" approach to new observations.

Likely, more observing systems will be proposed than can be carefully evaluated by COSSEs. Existing COSSEs may be used to help identify which proposed observing systems to test. USGCRP can also request the testing of specific observing systems that are considered of high enough national importance based on the results of Activities 1 and 2. Large investments in observations may be required to be evaluated using independent COSSEs.

COSSEs are useful not only before a new measurement begins, but are also relevant to evaluating the performance of a new measurement after it begins. For example, in situ observations may be changed in location or instrumentation based on appropriate analyses. Currently, COSSE capability at the agencies is in the very early stages of development. Early efforts in expanding this capability would lead to more rapid progress on all of the activities.

Most but not all climate science areas will be sufficiently developed to support realistic COSSE research. In cases where too little is understood to quantify requirements or estimate uncertainties and variability, alternative methods for utility and requirements will need to be developed. Such alternative methods will typically lead to larger uncertainty in cost/benefit analysis in Activity 4, as well as economic value studies in Activity 5. Over time as climate research in these areas advance, they will be able to move toward COSSEs and more rigorous analysis in Activities 4 and 5.

Activity 4 Engineering Studies of Cost and Likelihood of Success

This activity will focus on carrying out engineering studies of the economic cost of the observing system measurements, including the likelihood of each measurement approach to succeed. Often there will be a tradeoff between cost and likelihood of success for different climate measurement approaches. There will also be a tradeoff between the cost of the measurement and its ability to meet accuracy, sampling, and algorithm requirements. The key for expensive projects is that this level of activity is carried out prior to operational investments.

The engineering cost and success studies will typically be carried out or commissioned by the Agency that would provide the observation. This type of expertise already exists within most of the USGCRP agencies. Coordination across the newly developing COSSE community can assure robust and comparable results from these individual agency activities, improving likelihood of success of the final efforts.

In some cases, the desired observational capability will either not exist, or be prohibitively expensive (as judged in Activity 5). In these cases, further investment in technology development is indicated, with later re-evaluation of the measurement as new technological capabilities evolve. NASA Earth observation programs have used a version of such development in their technology development program, particularly the Instrument Incubator Program (IIP). Ideally, the amount of such investment can be tied to the results of the other activities, including economic value studies. In this sense, these activities are iterative over time as technological advances provide new capabilities of earth observations relevant to climate change.

Activity 5. Long Term Climate Observation Improvement Economic Value Studies

Weather prediction and other operational Earth observation services already have extensive efforts to evaluate and demonstrate their economic value to the nation. Since a climate observing system would be much more expensive than a weather observing system (10 times more variables to measure at 10 times the accuracy), the nation will require an improved understanding over time of the economic value of its climate research investments. To date, there has been only one agency announcement to support this type of research for long term climate change (NASA's Applied Sciences program in early 2016).

A few published studies of seasonal to inter-annual climate forecast value have been provided, but only 2 published papers to date have examined the economic value of improved long term climate observations (Cooke et al. 2014, 2015). A third paper has, however, examined the economic value of narrowing uncertainty in climate sensitivity, and found similar results to the first two papers (Hope, 2015). This type of study differs substantially from past efforts in weather and seasonal to inter-annual prediction. Further development of such studies would help the nation better understand the value of its investment in a rigorous long term climate observing system along with the analysis and climate prediction research required to take advantage of such a system for improved societal decisions relative to climate change.

As climate science advances, any long term societal commitment to climate research will require constant evaluation of cost versus benefit. Such studies would provide a critical part of that evaluation over time. They would also provide an improved communication between the climate science community, the administration, congress, and the nation on important future investments in climate research.

Activity 1 is needed immediately to support and prioritize efforts in all of the other activities. USGCRP agency investments expanding capability for Activities 3 and 5 could begin even before Activity 1 is complete, given the limited capabilities that currently exist, and the extended time it can take to develop a full COSSE capability. Early targets for these activities could be high priority climate science uncertainties in the recent IPCC AR5 report. The first part of Activity 2 could also begin in parallel with Activity 1. Leadership of the respective agencies should coordinate which efforts can be funded jointly to assure that the efforts serve both USGCRP and the agency priorities.

The entire effort to design a climate observing system is a major challenge. The best way to address such a large challenge may be to prototype the needed activities for a few high priority quantified science objectives as a learning experience, followed by expansion to a larger set of science objectives based on lessons learned with the first few. The running of COSSEs before any significant investment in new observations could significantly improve the likelihood for success of the proposed mission. However, the proposed COSSE approach should not be used to stall or hinder any currently proposed observing capabilities or plans.

4.3 Final Decisions on Climate Measurements

In our current U.S. government structure, the funding of specific observing systems will always be a joint decision of individual agencies, congress, and the administration. The proposed path ensures that any observations either designed for climate or potentially useful for climate will be critically evaluated for their ability to meet one of three goals: monitoring the Earth, advancing climate processes or improving climate projections. The organization of observing systems will be designed in such a way as to assure continuity, allow for testable hypotheses and include information that can support societal decisions.

A challenge in achieving such an observing system remains that none of the USGCRP agencies has climate change as its top priority, with most agencies having climate change as third, fourth, or lower priority. In this case a "curse of the commons" adds to the challenge. No agency fails its primary mission if our climate change future remains uncertain. Nevertheless, it is the responsibility of climate scientists across these agencies to present as clear a vision as possible of observing system measurements that are needed to narrow uncertainties in climate predictions, projections, and societal decisions while at the same time that represent a high economic return on investment for the nation and the world.

4.4 Key Activities to Support Advancement of Climate OSSEs

Current climate OSSE capabilities do not exist. A number of tasks have been identified to develop an appropriate climate OSSE structure, including review of existing, supporting efforts and evaluating existing observing capabilities.

Task 1: 6 months. Identify and review existing methods for evaluation of observing systems.

Task 2: 18 months Evaluate existing observing systems with respect to their ability to address the Key Challenges. This will involve national and international experts on the specific Key Challenges and should be carried out in conjunction with WCRP.

Task 3: 12 months Post for review all summary documents for any proposed or testable hypotheses/goals related to the Key Challenges. Meetings with relevant parties and reports will be carried out in conjunction with existing programs to develop quantified science objectives as hypothesis tests or goals and prioritization of the objectives.

Task 4. Part 1. 9 months. Develop a website with dynamic links to existing reports and studies on observational climate needs and COSSEs. This task includes a system for maintaining the information in the website.

Task 4. Part 2. 18 months Determination of gaps and synergies of existing observations and future planned observations with the quantified science objectives developed in Task 2..

Task 3: 36 to 60 months. Design and funding of COSSE groups to evaluate proposed observing systems. COSSE groups can either be funded via a proposal system or established by agencies as additions to existing weather or other OSSE efforts. Improve COSSE tool development during Task 2.

Task 4: 36 months. Given the large number of potential measurements, an extended period of time would be required for the agencies to evaluate cost and success probabilities for measurement approaches.

Tasks 5: 60 months. This is a new research area and requires tool development based on existing economic integrated assessment models (IAMs). It also requires time for development of collaboration between economics and climate science researchers. This will be an evolving effort over time, likely starting modestly with a few climate measurements and growing as research results are published that spur additional efforts for other climate measurements.

Bi-Annual reports to the USGCRP on progress will include the following tasks:

1. Identification and summary of all major reports both nationally and internationally on climate observations.
2. Report on efforts to develop priorities and testable hypotheses.
3. Identification and summary of all major national and international observing systems that support climate—both existing and planned.
4. Report on COSSE progress and results.
5. Report on usefulness of current and proposed observations (NOSIA-III-type analysis).

This paper outlines a major effort to begin the careful planning of an observing system that supports climate priorities. The emphasis of this approach is on reducing uncertainties in our understanding of climate.

5.0 Planned Collaboration

Key partners in this effort would be climate modeling and analysis groups. The science priorities and testable hypotheses should be identified first (steps 1 and 2). Initial discussions would be to evaluate existing efforts to develop climate science priorities and inventory observing systems based on whether they are existing, needed, planned or considered observing systems. Further discussions will focus on developing testable hypotheses in climate science that are currently observationally limited. Collaboration and interactions with professional science organizations, including AMS, AGU and EGU will be particularly important for engaging the broad scientific community in both establishing priorities and evaluating the effectiveness of observing systems.

National groups:

NOAA (e.g. HQ, GFDL, NCDC, ESRL, TPIO, SAB, AOML)
NASA: (e.g. HQ, GSFC, JPL, GISS, Langley)
DOE (e.g. ARM, Renewable Energy)
NSF (e.g. HQ, NCAR)
EPA
DoD
Universities (e.g. Harvard, Michigan, NCSU, GaTech, CU, CSU, U Wash., U. Wisc Madison, Duke, UAH, Utah, AZ, OK)
AMS (STAC) and AGU
National Academies

International groups:

World Climate Research Program / ICSU / IOC
Hadley Center (UK) and ECMWF's new climate office
IPCC
WMO
EGU
Arctic Monitoring Assessment Program (Oslo)
Max Planck (Germany)
Indian Institute of Tropical Meteorology
Canadian Centre for Climate Modeling and Analysis

Several of these groups have already started down paths of identifying research priorities, although most have done little to get specific about observational needs and testable hypotheses. The best of the work from each of these groups can guide the structure for proceeding. WCRP's Grand Challenges (Clouds, Ice, Extremes, Sea-level and Water as Grand Challenges) can serve as a useful way to organize observational requirements. NASA's preparatory discussions on critical requirements in advance of their decadal survey can serve as a model for how community discussions can identify key climate issues that are currently limited by observations. The goal of this project will be to leverage what has already been done and bring the community together over the next 18 months to identify the key climate priorities, and where possible, develop observational requirements and testable hypotheses. This 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 would engage the consumers of climate observations and work to identify priorities to significantly advance our climate observing system. The discussions and evaluation will foster new, cost-effective observing systems and support an integrated, science driven approach to planning an observing system that supports the highest priorities in climate change science.

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