A Quantitative and Objective Capability for Designing and Evaluating Earth Observing Missions

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Description. The climate research community requires an objective and quantitative capability to design climate observing systems and establish their requirements so as to maximize scientific value in a cost-effective way. The tool should be a "climate OSSE" and should be based in standard methods of Bayesian uncertainty quantification.

1. *What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?*

A key challenge for the Earth Science programs at NASA and NOAA is the development of an objective and quantitative capability to design climate observing systems appropriate to testing climate models according to their predictive capability[1] and to assure their maximum economic benefit. The challenge can be answered with a program in Climate Observation System Simulation Experiments—"climate OSSEs" —an idea taken from the numerical weather prediction community. In a weather prediction OSSE, simulated data of a prospective weather instrument are assimilated into a weather prediction system to examine whether and to what degree the data might improve prediction and what the requirements on the prospective instrument should be. An OSSE is undertaken by most major weather prediction centers around the world when considering new instrumentation. The same capability for designing and evaluating observing systems can be developed for *climate* by the Earth Science programs of NASA and NOAA.

Up to the present, climate observing programs have chosen space missions in large part based on the intuitive judgment of the best experts available. Nonetheless, the subjective and qualitative aspects of the decision making entail disputes in the climate community and the perception of undue influence by parties with non-scientific interests in the outcome of the decision. Also, requirements on mission architecture, spatial-temporal-spectral coverage, and on the accuracy and precision are left to the judgment of committees and science teams. The result is a community that regularly questions itself regarding the missions it selects and revises the requirements of its selected missions. There is a clear need for an *objective and quantitative* capability to help design missions and evaluate the capabilities and cost-effectiveness.

In a climate OSSE, a climate model (or ensemble of independent climate models) that can simulate the data of a prospective mission and can generate the predictions declared as the scientific goal of that mission are subjected to uncertainty quantification. The uncertainty quantification must sample the generally acknowledged uncertain physics, chemistry, and biology of the climate relevant to the scientific goals of the mission. The realizations of physics, chemistry and biology that produce hind-casts that compare most favorably with actual data are

[1] Goody et al., *Bull. Amer. Meteor. Soc.*, 83, 873–878.

given more serious consideration in arriving at final scientific conclusions. Observation error reduces the efficacy of the comparison of model hind-cast and data, and inappropriate coverage can greatly inhibit the optimality of information needed to reduce uncertainty in the mission's scientific objective. A climate OSSE can analyze different configurations of instrumentation and varying levels of observation error to quantify the impact of both on a final scientific conclusion for the mission. The methods are based in Bayesian uncertainty quantification and have been described in the peer-reviewed literature[2]. They allow for objective determinations of spatial-temporal-spectral coverage of observations, their required accuracy and precision, and to what degree they may be redundant with other data. They can analyze the value of an observation for traditional as well as non-traditional objectives, such as multi-decadal temperature change, extreme weather, fresh water availability, the spread of disease, forced migration, and the overall economic benefit to global human society.

Implementation of a climate OSSE can take many forms. A climate OSSE requires (1) a core model ensemble that can represent all prior uncertainties in the climate relevant to a prospective mission's objective, (2) the ability to simulate data like that to be produced by a prospective mission, and (3) the ability to produce predictions corresponding to the objective of a prospective mission. All three can be implemented in varying degrees of complexity, meaning that anyone from an individual researcher to a substantial institute can undertake a climate OSSE. While in the end only a sophisticated effort undertaken by an institution can deliver the conclusive climate OSSEs needed for overall mission evaluation, the parameters around such efforts have yet to be determined. Such parameters are, for example, what model or ensemble of models should be considered as the core, whether or not to simulate data in all of its detail or instead produce trends and variability in atmospheric variables that can be retrieved from the data, and what new models must be connected to the core model to generate predictions related to human impact such as forced migration, spread of disease[3], and economic value in general[4].

2. Why are these challenge/questions timely to address now especially with respect to readiness?

The climate research community is already intuitively familiar with the idea of a climate OSSE inasmuch as it has already undertaken to mine existing climate data to improve constraints on equilibrium climate sensitivity[5]. Small efforts in perturbed physics ensembles of domestic climate models have been completed[6], so there already exists expertise in the research community in Bayesian uncertainty quantification[7].

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[2] Rougier, *Clim. Change*, 81, 247–264, 2007; Rougier and Sexton, *Phil. Trans. R. Soc. A*, 365, 2133–2143, 2007; Huang et al., *Proc. Nat. Acad. Sci.*, 108, 10405–10409, 2011

[3] USGCRP Climate and Health Assessment, globalchange.gov/health-assessment, 2015.

[4] Cooke et al., *Environ. Syst. Decis.*, 34, 98–109, 2014.

[5] Hall and Qu, *Geophys. Res. Lett.*, doi:10.1029/2005GL025127, 2006; Fasullo and Trenberth, *Science*, 338, 792–794, 2012.

[6] Fasullo et al., *Curr. Clim. Change Rep.*, doi:10.1007/s40641-015-0021-7, 2015.

[7] Jackson, *J. Phys.: Conference Series*, **180**, doi:10.1088/1742-6596/180/1/012029.

Implementation of a climate OSSE will almost certainly take the form of both a small research grant program and the development of an institute that will construct a large, sophisticated tool. The former would be undertaken for the sake of exploratory studies on the potential value of new observing systems; the latter would be undertaken for the sake of objective evaluation of missions. Before initiation of a program of climate OSSEs, however, a formal discussion should be held among representatives of modeling centers, scientists with expertise in perturbed physics ensembles of climate models, interested investigators from existing climate observing missions, and representatives of climate observing/monitoring programs of NASA and NOAA to develop a plan for the outlines of a climate OSSE program.

Because a climate OSSE—like Bayesian uncertainty quantification—in general depends on the completeness of the hypotheses to be tested and therefore awareness of all physical, chemical and biological processes relevant to climate change, a climate OSSE cannot answer every mission undertaken by the Earth science programs inasmuch as the community most certainly is not aware of all processes relevant to climate change. For this very reason, there will always be a need for missions of exploration, to obtain data at the frontiers of technological capability, so that human awareness of those unknowns can be expanded and the newly identified processes incorporated into climate models leading to a continually evolving program of climate OSSEs.

3. Why are space-based observations fundamental to addressing these challenges/questions?

At present, Earth science programs are undertaking efforts at climate monitoring for the sake of testing models according to their predictive capability. Climate models have not improved in their ability to predict climate change since the Charney report[8], and the uncertainties of the climate system responsible remain largely unchanged. Because the unknowns in the physics, chemistry and biology of climate are near universally acknowledged and still weakly unconstrained, a program of climate OSSEs is ideally suited to the design and valuation of climate *monitoring* systems. Considering that the Global Climate Observing System[9] of WMO, the NASA Decadal Survey mission CLARREO[10], and other efforts worldwide are being considered for climate monitoring for the sake of testing climate models, it is incumbent upon the Earth science community to incorporate a program in climate OSSEs now.

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[8] National Academy of Sciences, *Carbon Dioxide and Climate: A Scientific Assessment*, 1979.

[9] Bodeker et al., *Bull. Amer. Meteor. Soc.*, doi:10.1175/BAMS-D-14-00072.1, 2015.

[10] Wielicki et al., *Bull. Amer. Meteor. Soc.*, 94, 1520–1540, 2013.