<u>Title</u>: **The Scientific and Societal Challenge of Reducing Uncertainty in Climate Sensitivity**

<u>White Paper Description</u>: *The next decade will be critical to improve the ability of current and future observations to constrain the factor of 4 uncertainty (90% confidence) in equilibrium climate sensitivity. This uncertainty alone causes a factor of 10 or more uncertainty in future economic impacts of climate change. Increased observation accuracy is essential.*

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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?

The uncertainty range for climate sensitivity has not changed significantly since the 1979 NRC Charney report on climate change. In the forward to that report, Vern Suomi wrote about climate change "*In order to address this question in its entirety, one would have to peer into the world of our grandchildren,* ***the world of the twenty-first century"***. We are now 15 years into the 21st century, more than 35 years since the Charney report. Our uncertainty of climate sensitivity remains the same, despite 35 years of advances in modern observations, paleo observations, and Earth system models. We have, however, developed a much more rigorous understanding of the sources and magnitude of uncertainty in climate sensitivity.

The 2010 U.S. Social Cost of Carbon Memo is the U.S. interagency guideline for understanding potential future climate change impacts. The document concludes that the largest uncertainty in future impacts is caused by uncertainty in climate sensitivity. The amount that the globe warms is the pacemaker for almost all other climate change, whether sea level rise, drought, floods, agriculture, health, or species loss. The report also concludes that there is a roughly quadratic relationship between amount of warming and amount of economic impact. This nonlinearity is caused by the fact that current societal infrastructure is designed to handle climate natural variability. When climate change causes those historical limits to be exceeded, large and nonlinear economic impacts ensue. The quadratic relationship suggests that on the longest time scales, uncertainty of a factor of 4 in climate sensitivity leads to a factor of 16 uncertainty in economic impacts. This is not true for the next few decades, but becomes increasingly true as time scales increase to 50 or 100 or 200 years from now. Much of the uncertainty about climate change mitigation efforts is tied to uncertainty about future economic impacts.

Why has it been so difficult to narrow the uncertainty in climate sensitivity? Five IPCC reports have extensively examined this challenge using modern observations, paleo observations, and the range of results using climate and Earth System models including Perturbed Physics Ensembles. All three approaches suggest a similar uncertainty in climate sensitivity. The dominant cause of this uncertainty continues to be cloud feedback, in particular low cloud feedback (IPCC, 2013). One of the major reasons is that explicit modeling of low clouds using Large Eddy Simulation (LES) models typically requires grid box scales of ~ 10 meters, compared to a highest resolution of ~100 km in global climate models.

Solution of this challenge requires advances in both modeling and observing capabilities. For observations related to the Decadal Survey, there is a need for advances in both cloud process observations as well as long term decadal change observations. Neither short term cloud process observations alone, nor long term climate change observations alone can solve this challenge. Nor can observations alone or models alone solve this challenge. NASA can clearly provide unique contributions in the area of improved process observations from space (e.g. A-train) and long-term climate change observations from space (e.g. CERES, MODIS, CALIPSO, CloudSat, GPM). A key question to consider is the relative contributions and requirements for improved long term climate records of clouds, aerosols, and radiation versus improved process observations of the same. Neither alone will be sufficient. We note also that solution of the cloud feedback and climate sensitivity challenge is also related to solution of the anthropogenic aerosol indirect effect uncertainty. Observed decadal changes in clouds must be separated between anthropogenic aerosol induced change and anthropogenic greenhouse warming induced change.

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

Given the inability to narrow uncertainty in cloud feedback during the last 35 years, one might be tempted to conclude that either a) the problem is too hard or b) it will take too long to solve. A pair of recent studies (Cooke et al. 2014, 2015) examined the world economic value of moving forward by ~ 15 years the ability to narrow uncertainty in climate sensitivity. The result of both studies suggested a value of ~ $10 Trillion U.S. dollars to society if this could be accomplished. Sensitivity studies showed that the economic value of doing so depended little on when it was done: only on the fact that you could advance progress by 15 years. This seems puzzling until you realize that this is in fact a "delta" calculation: we are not estimating total climate change impacts, only the value of moving forward knowledge by N years to enable better societal decisions to deal with these impacts. This suggests that the "value" of reducing uncertainty in climate sensitivity 15 years sooner than "science as usual" is roughly $10 Trillion dollars. NASA's entire earth science budget is ~ $1.7B per year: 6000 times smaller than the potential gain for society. The investment leveraging potential of reducing uncertainty in climate sensitivity sooner rather than later is immense, and the Decadal Survey should seriously consider how to accomplish this goal.

Since the last decadal survey, there are several technological advances that have matured into readiness to improve our attack on this challenge. The ***First*** advance, is that computational capability now allows the potential to run LES cloud models at 1000 km scale for short simulations (days). This allows for the first time a true overlap of climate models and cloud models all the way to LES scales. Global 3-D 1 km cloud resolving models have also been run for periods of up to a year. Multi-scale Modeling Framework (MMF) climate models have developed ways to merge 2-D cloud resolving models within 3-D climate models. Further advances in the next decade mean that testing cloud modeling in climate models is at the cusp of major potential advances in cloud modeling. Will the observations be there to test them?

The ***Second*** advance is that the 2007 Decadal Survey CLARREO mission has spent the last 7 years working on demonstration instruments with NIST calibration verification to allow improvements in calibration for both narrowband and broadband spaceborne sensors by a factor of 5 across the entire thermal infrared spectrum and a factor of 10 across the entire reflected solar spectrum (Wielicki et al, 2013). These advances are critical if we are to verify cloud and radiation decadal changes to the accuracy needed to detect cloud feedback (Wielicki et al., 2013) sooner than our current observations can provide. Figure 1 below shows the relationship between accuracy and time to detect decadal change of shortwave cloud radiative effect, the dominant signal for low cloud feedback (Soden et al. 2008, Wielicki et al. 2013). Using CLARREO to calibrate CERES can accelerate results by 20 to 30 years depending on the uncertainty desired.

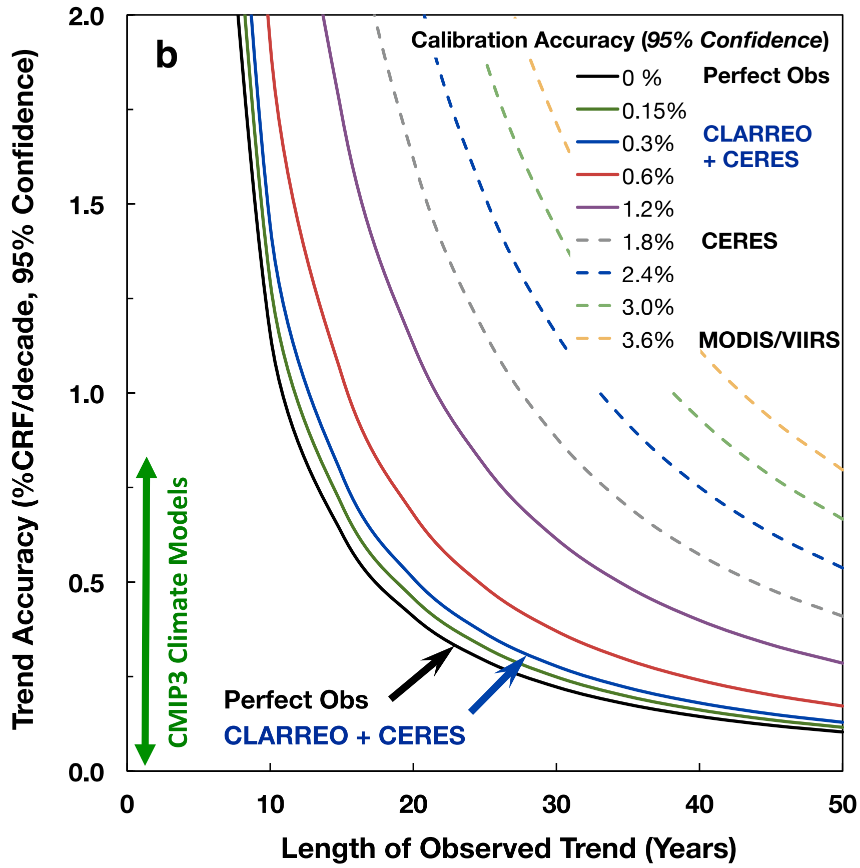

Figure 1. Trend uncertainty in shortwave cloud radiative forcing (CRF) per decade (the dominant signal of low cloud feedback) versus instrument calibration accuracy.

The recently released NRC report "Continuity of NASA Earth Observations from Space: A Value Framework" (2015) shows an example in Appendix C of how narrowing uncertainty in climate sensitivity can be understood as a Quantitative Earth Science Objective and demonstrates the value of using higher accuracy reference calibration systems such as CLARREO in orbit to enable more accurate CERES radiative fluxes (factor of 5) and MODIS cloud properties (factor of 10). Lack of such accuracy in the last 35 years of cloud feedback observations is a major reason for lack of progress to date. Serious consideration should also be given to the need for long term climate change observations of space based lidar (e.g CALIPSO) and radar (e.g. CloudSat) for cloud properties (compared to cloud imagers such as MODIS or VIIRS). Lidar in particular provides the most rigorous observation of cloud fraction and cloud height: the two cloud variables considered to be most critical for cloud feedbacks in the reflected solar and infrared. For annual mean zonal and global cloud observations, nadir lidar provides sufficient sampling to reduce sampling uncertainty to levels below that of natural variability. These active sensors should be evaluated for continuity requirements using the new NRC Continuity Framework.

The ***Third*** advance is that efforts to demonstrate new lidar (high spectral resolution), radar (multi-wavelength), and radiometer (multi-angle polarimeter) technologies have demonstrated new tools to improve aerosol and cloud process observations from space (e.g. ACE from the 2007 Decadal Survey).

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

Because clouds and radiation are highly variable in space and time, only space based global observations can provide constraints on global cloud feedback. The decadal signals of clouds and aerosols that drive global change are subtle and require both rigorous calibration over time as well as sufficiently complete sampling to observe. Surface and in-situ observations are critical for process studies, but cannot provide global change constraints and verification that climate models can produce the correct cloud feedback for the correct cloud types.

References

Cooke, R., B. A. Wielicki, D. F. Young, and M. G. Mlynczak, 2014: Value of Information for Climate Observing Systems. Journal of Environment, Systems, and Decisions, *Environ Syst Decis*, 34, 98–109, DOI 10.1007/s10669-013-9451-8.

Cooke, R., A. Golub, B. A. Wielicki, D. F. Young, M. G. Mlynczak, R. R. Baize, 2015: Real Option Value of Earth Observing Systems. *Climate Policy*, in press.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovern- mental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IWG SCC (Interagency Working Group on Social Cost of Carbon, U.S. government) (2010). Social cost of carbon for regulatory impact analysis under executive order 12866, Appendix 15a, Washington DC. http://www.epa.gov/otaq/climate/regulations/scc-tsd.pdf

National Academy of Sciences. 1979. Carbon Dioxide and Climate: A Scientific Assessment. Washington, DC: The National Academies Press.

National Academies of Sciences, Engineering, and Medicine. 2015. Continuity of NASA Earth Observations from Space: A Value Framework. Washington, DC: The National Academies Press.

NRC, 2007: Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond. National Academy Press, 428 pp

Soden, B. J. , I. M. Held, R. Colman, K. M. Shell, J. T. Kiehl, and C. A. Shields, 2008: Quantifying climate feedbacks using radiative kernels. J. Climate, 21, 3504–3520.

Wielicki, B.A., D. F. Young, M. G. Mlynczak, K. J. Thome, S. Leroy, J. Corliss, J. G. Anderson, C.O. Ao, R. Bantges, F. Best, K. Bowman, H. Brindley, W. Collins, J. A. Dykema, D. R. Doelling, D. R. Feldman, N. Fox, X. Huang, R. Holz, Y. Huang, Z. Jin, D. Jennings, D. G. Johnson, K. Jucks, S. Kato, R. Knuteson, G. Kopp, D. P. Kratz, X. Liu, C. Lukashin, A. J. Mannucci, N. Phojanamongkolkij, P. Pilewskie, S. Platnick, V. Ramaswamy, H. Revercomb, J. Rice, Y. Roberts, C. M. Roithmayr, F. Rose, S. Sandford, E. L. Shirley, W.L. Smith, Sr., B. Soden, P. W. Speth, L. Strow, W. Sun, P.C. Taylor, D. Tobin, X. Xiong, 2013: Climate Absolute Radiance and Refractivity Observatory (CLARREO): Achieving Climate Change Absolute Accuracy in Orbit. *Bull. Amer. Met. Soc.*, **93**, 1519-1539.