CLARREO Science Questions

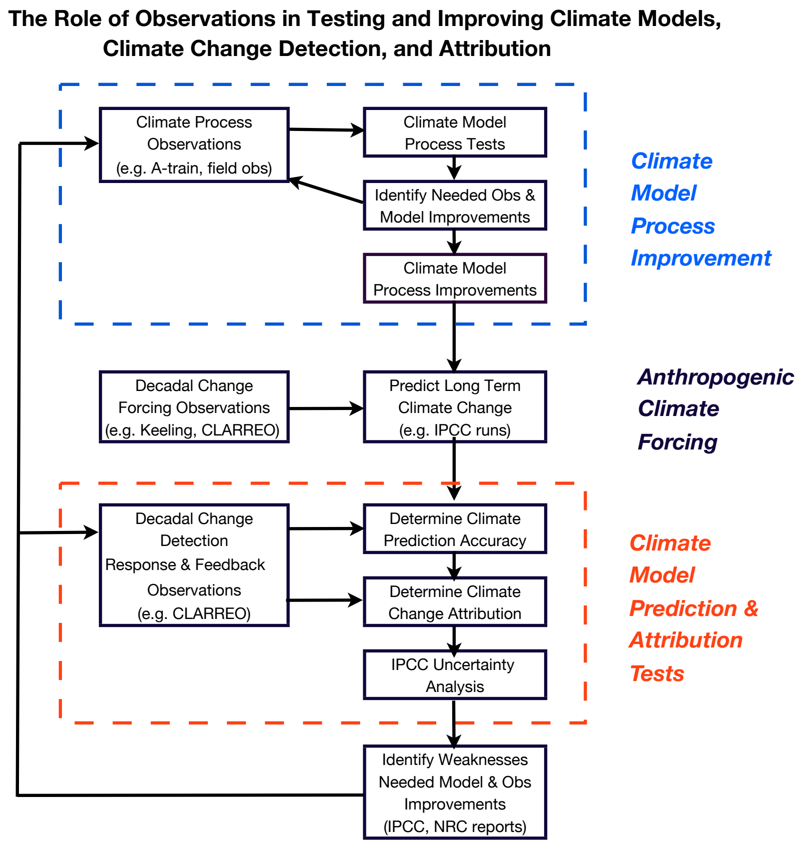
Given the rapid increase in climate forcing from carbon release, how is the Earth's climate system changing? Recognizing the impact on both scientific understanding and societal objectives resulting from the irrefutable, high accuracy, SI traceable Keeling CO_2 record, what measurements obtained from space would constitute an analogous high accuracy, SI traceable climate record defining the global *response* of the climate system to the anthropogenic and natural *forcing?* These are fundamental questions addressed by the CLARREO mission. The societal impact of these scientific questions can be summarized in two CLARREO societal objectives:

I. ***Societal objective of establishing a climate benchmark:***
The essential responsibility to current and future generations to put in place a benchmark climate record, global in its extent, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards *on-orbit*.

II. ***Societal objective of the development of an operational climate forecast:***
The critical need for climate forecasts that are tested and trusted through a disciplined strategy using state-of-the-art observations with mathematically rigorous techniques to systematically improve those forecasts.

The overarching scientific questions and societal objectives summarized above lead directly to more specific science questions. These specific questions result from the tightly coupled nature of climate observations and the climate models used to make climate predictions. The schematic on page 2 shows this relationship and demonstrates the fundamental difference between most NRC Decadal Survey Missions (climate process missions shown in blue) and CLARREO which is focused on climate decadal change observations (shown in black for climate change forcing, and shown in red for climate change detection, determination of climate model accuracy and for climate change attribution).

The critical and unique role of CLARREO is to serve as the SI traceable benchmark for decadal climate change. The diagram illustrates how the accuracy of this decadal change record directly controls the ability to determine the accuracy of climate change forcing, detection, attribution, and climate prediction accuracy. While process missions are essential to improving the underlying climate model physics and biology, only decadal change observations can determine the accuracy of the resulting climate change predictions. *A decadal time scale prediction must be tested on decadal time scale observations. Climate change detection and attribution to anthropogenic forcing also rely critically on decadal time scale observations.* The recent IPCC, NRC Decadal Survey, and CCSP assessment reports are all examples of examining climate model process and decadal change tests, resulting in identifying and prioritizing key weaknesses in climate models and climate observations. These reports also rely on the combination of accurate climate change observations and climate model predictions for critical studies of both



climate change detection as well as climate change attribution to natural variability or anthropogenic sources. The most critical weakness identified in all of the reports is the limited accuracy of decadal change observations. In Chapter 3 of the NRC Decadal Survey report it states that "Design of climate observing and monitoring systems from space must ensure the establishment of global, long-term records, which are of *high accuracy*, *tested for systematic errors on-orbit*, and *tied to irrefutable standards* such as those maintained in the U.S. by the National Institute of Standards and Technology". CLARREO is a new "calibration first" approach that addresses the critical weaknesses in the accuracy of current spaceborne observations. Because it covers the entire solar and infrared spectra critical to the Earth's energy balance, CLARREO will provide this accuracy for most of the climate variables essential for climate change forcing, detection, response, attribution, and prediction. The forcing and response observations are the same observables critical to studies of climate change detection and attribution. In some cases CLARREO will provide these observations by a direct benchmark of CLARREO spectral radiances, in other cases by CLARREO in-orbit intercalibration of other spaceborne instruments not sufficiently accurate for climate change. CLARREO intercalibration of operational instruments will provide the first anchor for retrospective climate focused re-analyses. This new capability should enable the first re-analyses free of the major instrument change artifacts that degrade current climate re-analysis efforts.

The CLARREO observations alone cannot be used to predict future climate change or to attribute such change to anthropogenic forcing. Nor can any climate observations. It is only the combination of climate observations and climate models that can provide climate change attribution and predictions with the confidence and scientific rigor needed to guide societal decisions. As a result, the CLARREO science questions are posed in a way to show both the climate model and the observation aspects of each question. The climate model prediction uncertainties will drive science priorities. CLARREO is unique in that its science requirements are being determined using a new approach: climate Observing System Simulation Experiments. The Climate OSSE approach provides a much more rigorous link between prediction uncertainties and observation improvements. OSSE approaches have been used for weather prediction observing systems, but CLARREO will be the pioneer of such approaches for climate detection, attribution, and prediction.

The observation portions of the CLARREO science questions will lead to the mission instrument, orbit, and sampling requirements. These observation requirements will drive the engineering estimates of the cost, schedule, implementation, and risk. The trade space for CLARREO decisions on mission requirements is a 2 dimensional space of science impact versus implementation cost and risk. This can be thought of simply as a chart with Impact on the y-axis versus Cost on the x-axis. The CLARREO pre-phase A definition studies are targeted at clarifying this Science/Cost trade space to define rigorous level 1 mission requirements. CLARREO science questions are categorized by the expected CLARREO contribution as *Critical*, *Important*, or *Substantial*. Science impact combines both the importance of the climate science question itself, as well as CLARREO's ability to provide data unique to its solution. CLARREO costs include both cost and technological risk factors. But because providing a climate observation benchmark is so critical to future societal climate change decisions, there is an unusual sense of urgency to begin the CLARREO benchmark. Therefore the time schedule to launch all or portions of the CLARREO mission are also key to implementation decisions. There is a potentially large societal "cost" to delay of CLARREO. As a result of the CLARREO mission goals and our current understanding of the relevant instrument technologies, we classify CLARREO implementation approaches into three major types:

(i) science questions that CLARREO will address directly with current technology and without the need for any other observations. This category is primarily the mid-infrared spectra (~ 3 to 15 μm wavelengths), and GPS.

(ii) science questions that CLARREO will address directly with expected definition study and IIP confirmation of recent advances in metrological technology and sampling strategies. This category is primarily applicable to the new observations of the Far-Infrared Earth emitted spectra (~ 15 to 100 μm) and the spectra of solar radiation reflected from the Earth and incident on the Earth (~ 0.3 to 2.5 μm).

(iii) science questions that CLARREO will address in combination with other satellite solar and infrared sensors such as operational weather sensors, most commonly using a transfer of CLARREO SI traceability to other instruments through intercalibration in orbit. Examples here would include current and future instruments such as AIRS, CrIS, IASI, MODIS, VIIRS, and CERES.

Using the approach described above, we have identified 16 climate science questions that CLARREO is expected to make either **critical**, *important*, or substantial contributions to. We refer to this contribution as the CLARREO Science Impact. In some cases, the question itself

Table 1. CLARREO Science Questions

Science Question ("change over time" = decadal change)	CLARREO Science Impact	CLARREO Observable (SI traceable)	CLARREO Implementation Approaches
Climate Forcing: Natural and Anthropogenic			
1) How is aerosol direct effect radiative forcing changing over time? How accurately is this forcing change represented in climate models?	**Critical**	Solar Reflected Spectra Polarization	(ii), (iii)
2) How is solar radiative forcing changing over time? How accurately is this forcing change represented in climate models?	**Critical**	Total and Spectral Solar Irradiance	(i), (iii)
3) How is the anthropogenic greenhouse gas radiative forcing changing over time? How accurately is this forcing change represented in climate models?	*Important*	Mid IR Spectra	(i)
4) How is radiative forcing due to land use changing over time? How accurately is this forcing change represented in climate models?	*Important*	Solar Reflected Spectra	(iii)
5) How is the aerosol indirect effect radiative forcing changing over time? How accurately is this forcing change represented in climate models?	Substantial	Solar Reflected Spectra Polarization	(iii)
Climate Response: Change Detection, Attribution, and Prediction Accuracy			
6) How is the vertical temperature and water vapor structure in the atmosphere changing over time? What part of the change is consistent with anthropogenic forcing? How accurately do climate models predict the changes?	**Critical**	Mid-IR Spectra GPS	(i), (ii), (iii)
7) How are cloud properties (fraction, optical depth, emissivity, height, temperature, phase, particle size) changing over time? What part of the change is consistent with anthropogenic forcing? How accurately do climate models predict the changes?	**Critical**	Mid-IR, Far-IR Spectra Solar Reflected Spectra	(iii)
8) How is the nadir infrared radiance emission spectra of the Earth at TOA changing over time? What part of the change is consistent with anthropogenic forcing? How accurately do climate models predict the changes?	**Critical**	Mid-IR Spectra Far-IR Spectra	(i), (ii), (iii)
9) How is the nadir solar reflectance spectra of the Earth at TOA changing over time? What part of the change is consistent with anthropogenic forcing? How accurately do climate models predict the changes?	**Critical**	Solar Spectral Irradiance Solar Reflected Spectra	(ii)
10) How are the solar reflected, infrared emitted, and net radiative fluxes at TOA changing over time for clear and all-sky? What part of the change is consistent with anthropogenic forcing? How accurately do climate models predict the changes?	**Critical**	Mid-IR, Far-IR Spectra Solar Reflected Spectra	(iii)
11) How are the amplitude and phase of diurnal cycles of Earth emitted and reflected spectra changing over time? What part of the change is consistent with anthropogenic forcing? How accurately do climate models predict the changes?	*Important*	Mid-IR, Far-IR Spectra Solar Reflected Spectra	(i), (ii)
12) How is vegetation responding to climate change, including ocean color? What part of the change is consistent with anthropogenic forcing? How accurately do climate models predict the changes?	*Important*	Solar Reflected Spectra	(iii)
Climate Feedbacks and Climate Sensitivity			
13) What is the amplitude of cloud feedback? How accurately is it represented in climate models?	**Critical**	Mid-IR, Far-IR Spectra Solar Reflected Spectra	(iii)
14) What is the amplitude of water vapor feedback and lapse rate feedback? How accurately is it represented in climate models?	**Critical**	Mid-IR, Far IR Spectra GPS	(i), (ii)
15) What is the amplitude of surface snow and ice albedo feedback? How accurately is it represented in climate models?	**Critical**	Solar Reflected Spectra	(iii)
16) How is the net radiative energy balance of the earth, a key measure of climate sensitivity, changing over time? How accurately is it represented in climate models?	**Critical**	Mid-IR, Far-IR Spectra Solar Reflected Spectra	(iii)

may be of critical importance, but CLARREO may only be able to make a contribution to its partial solution, in which case we list it as *important* or substantial CLARREO science impact. An example of this is aerosol indirect effect. In most cases, the science impact is driven by the science question itself, as derived from recent IPCC, NRC, or CCSP reports. Each question has a more complete description in Appendix A of the science question itself, its impact, and the likely CLARREO implementation approach. The science questions are grouped under three major climate science topics: climate anthropogenic forcing, climate response to the forcing which is at the heart of climate change detection, attribution, and prediction accuracy, and finally climate feedbacks that determine climate sensitivity. This organization is similar to the structure of the IPCC report as well as NASA Earth Science strategic plans. Recognizing the tight linkage of climate model predictions and observations, each of the science questions are written as an observation question paired with a corresponding climate modeling question. In the Response section, this linkage of models and observations also provides an attribution question. While the questions are listed in the typical *forcing/response/feedback* order for logical simplicity, we note that CLARREO's largest science contributions will be in the *response/feedback* portion of the science questions.

Table 1 lists the 16 CLARREO science questions. The columns on the right of each science question indicate the CLARREO observations (SI traceable) relevant to that science question, as well as the potential CLARREO implementation approaches (i,ii, or iii above). While the CLARREO science questions themselves are not likely to change as a result of the pre-phase A studies underway, the CLARREO science impact and optimal implementation approaches may change as study results are completed. The phrase "change over time" in the science questions refers to decadal time scales for climate change.

CLARREO is expected to be one of the most cost effective of all the climate related decadal survey missions in terms of science impact. As can be seen in Table 1, CLARREO has the potential for unique value to decadal change observations needed for a wide range of critical climate science questions. The urgency for the CLARREO mission is a result of the rapidly growing societal challenge of current and future climate change. The urgent need to accurately predict climate change, to develop intelligent plans to minimize it, and to plan methods to adapt to it. This urgency is also a result of the growing realization in the climate science community of the critical need for higher accuracy decadal change observations than currently exist.

The timing of the CLARREO mission (*why now?*) is a result of recent advances in a wide range of scientific, metrology, and technological research. These advances combine to enable CLARREO to be a completely new type of climate mission. A mission focused on accuracy at decade time scales through two complementary methodologies: spectral radiance benchmarks, and intercalibration of other orbiting sensors. A mission focused on high spectral resolution and broad spectral coverage throughout the solar and infrared spectrum that drive the Earth's climate energy system and climate change. A mission able to leverage its capability across a wide range of climate science disciplines, and satellite earth observing systems. CLARREO will be the first mission capable of providing an anchor at decade time scales to a climate observing system which is currently an accident of international weather and research observing systems. As soon as the international science community attempts to “design” a climate observing system, CLARREO or something similar to it will undoubtedly be the cornerstone of that system. Every year we delay is a year lost in beginning that climate observing system. It is not an exaggeration to state that much of a true climate observing system will begin when CLARREO begins its radiance benchmarks, and when CLARREO begins calibrating other less accurate earth viewing sensors in orbit including the new weather, land, and ocean satellite systems.