The ACE Measurement Concept for Reducing Uncertainties in Climate Sensitivity and Understanding Cloud-Aerosol Interactions

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Motivation

In a response to the previous Decadal Survey Request for Information (RFI#1), we submitted the document entitled "*The Link Between Climate Sensitivity Uncertainty and Understanding Cloud-Aerosol Interactions*". In that document we discussed a long-standing issue that is known to be a primary contributor to uncertainty in predicted climate sensitivity [1,2,3]. Recent model intercomparisons *(e.g.,* AR5) recognize the marine boundary layer (MBL) cloud feedback as the leading source of uncertainty in climate prediction today. The spread in climate sensitivity among global climate models (GCMs) ranges from 1.5 to 6^{o} C. While a number of issues contribute to that spread, at least *50% of that uncertainty is due to differences in cloud feedbacks* among the models[4] and *approximately 75% of cloud feedback uncertainty is due to uncertainty in how marine boundary layer (MBL) cloud coverage will change as the climate warms*[5]. In particular, models that predict that marine boundary layer (MBL) clouds will decrease as the climate warms show a significantly positive climate sensitivity due to increased absorption of solar energy as MBL clouds decrease – a positive cloud feedback. Models that predict an increase in MBL clouds show a much less positive climate sensitivity where the increases in MBL clouds are a negative cloud feedback[6]. The persistent and large spread in climate sensitivity cannot be reduced until the MBL cloud feedback uncertainty (MCFU) is solved. This problem was the scientific theme of our previous response to the Committee and it is also our focus in this document.

Quantified Earth Science Objective

While it may be premature to expect that the MCFU problem can be completely solved using the modeling and observational approach we outline, *we reasonably estimate that the MCFU can be reduced by two-thirds* using a combination of the theoretical modeling constrained by the Earth Science Observations we propose herein. **In the "Value Framework" context, we therefore aim to reduce the climate sensitivity uncertainty (our Quantified Earth Science Objective or QESO) by (0.5*0.75*0.66) or approximately 25%, where we have used the quantitative estimates of the fraction of the climate sensitivity spread that is due to clouds (0.5) and the fraction of the cloud contribution that is due to MBL clouds (0.75).**

The MCFU problem has resisted solution by the community[2]. The difficulty is due to a lack of knowledge regarding the coupled physics and dynamics of the cloudy MBL[2]. The characteristics of the system at any instant are a particular solution to forcing from below (the ocean), above (the free troposphere) and within (aerosol and turbulence) the MBL. Fundamentally, the dynamics of the MBL respond to and drive the microphysical responses of the system yet the microphysical processes operating within the system ultimately feed back on the dynamics through downdrafts, entrainment, precipitation, and radiation[7]. This entire coupled, multi-dimensional system must be understood holistically in order to be simulated accurately on the global scale; and this understanding must extend across the entire dynamic continuum of spatial and temporal dimensions.

While understanding ultimately comes from theoretical exploration of the coupled system through numerical models[8] and analytical studies, observations *must* provide appropriate constraints to guide the theory. The set of observational constraints that have been possible with past and present earth observations have not proven sufficient. While valuable for broadly characterizing models and their shortcomings, current observations provide only limited insight into the highly uncertain relationships between air motions, aerosols, and microphysical processes – particularly those that contribute to precipitation formation – which models must represent. The earth science community is in the process of developing global models that can explicitly resolve cloud motions (down to scales of at least a few km) or parameterize these motions using so called PDF schemes[17] and which include representations of microphysical processes that depend on the cloud scale motions. It is the highly uncertain relationships between air motions, aerosols, and microphysical processes – particularly those that contribute to precipitation formation – that form the most significant stumbling blocks to improved understanding[7,8,9]. In this document therefore, we describe an observational suite that builds on lessons learned since the advent of the A-Train to describe how we can provide the necessary observational constraints.

Earth Science Target Focused Science Questions

We have classified our focused science questions in terms of the relevant earth science themes discussed in the RFI call. To address the issue of climate sensitivity listed in *Table 1* under **Theme II: Climate Variability**

and Change (Q1), the questions focus on how absorbed solar radiation at the surface changes due to changes in cloud cover but the answers to those questions depend on how cloud cover changes due to changes in MBL properties. For instance, for a given thermodynamic and large-scale forcing, 1) do modifications in aerosols result simply in changes to droplet number and albedo as predicted by the well known Twomey effect or, as simulated in recent[9] modeling work?, 2) do changes in aerosol result in dynamical changes that influence cloud cover or other macrophysical properties of the cloudy MBL that ultimately mitigates the first order effects of the aerosol as suggested by recent observational studies[10]? 3) How do the answers to the first two questions vary across the spectrum of large-scale environmental conditions?

Importance of Geophysical Parameters and Measurements

Our objective is to provide observational constraints on the questions we pose. We fully understand that reduced spread in climate sensitivity can only emerge when new understanding is created theoretically and confirmed through numerical simulation. However, *observational constraints over the full spectrum of the multidimensional space occupied by the natural variability of dynamics, thermodynamics, and the physical states within which boundary layer cloud systems evolve is equally necessary to guide those simulations*. We aim to achieve such a spectrum of observational constraints with the set of geophysical parameters that can be derived from the measurement suite listed in column 4 of *Table 1*. Our approach to observational requirements is to focus on a *threshold suite.* We view this threshold measurement suite as a foundation that, alone, advances the science objectives, and can be built upon with additional measurements (some also listed). These additional measurements could be provided by international partners, Earth Venture-class participation, etc. It is also important to note that the traceability we represent in Table 1 between geophysical parameters and measurements is notional to a degree. Knowledge of the geophysical parameters is the key aspect here and the instrument combination we discuss is the most straightforward path to them but other possibilities are certainly possible.

The geophysical parameters listed in column 3 of Table 1, form a comprehensive set of quantities from which the relationships between dynamics and local aerosol profiles and microphysical processes can be quantified and we address their traceability in the following paragraphs. We have discussed a multidimensional continuum created by the dynamics and thermodynamics of the boundary layer, the large-scale atmosphere, the microphysical processes, and the physical state of the cloud-free boundary layer represented by aerosol properties. It has proven exceedingly difficult to characterize the cloud-scale dynamical state of the MBL using space-based remote sensing. However, knowledge of this dynamical state across the cloud-dynamics continuum is fundamental to our goals. As we described in our response to RFI#1, the manner by which aerosols impact a cloud, all else being equal, is due to the initial droplet spectrum activated in an updraft near cloud base. *However, measurement of cloud base vertical motion at the cloud scale is not technologically possible from space*. Instead, a viable solution to this problem involves using Doppler radar measurements at the coarse (relative to the cloud scale) 1 km footprint combined with a cloud-scale description of cloud top dynamics (3d winds) provided by a stereo photogrammetric methods that builds on and advances measurements pioneered by the MISR instrument on the Terra satellite. Together, the Doppler velocity and the cloud-scale dynamics provided by photogrammetry or stereo imagery could be used in a retrieval algorithm to derive estimates (with uncertainty) of cloud base vertical motions. Our vision is to combine knowledge of cloud motions (including the estimated cloud base velocity) with knowledge of cloud, precipitation and aerosol geophysical properties. In combination, these data will be used to refine microphysical process representations and ultimately directly constrain microphysical process rates.

The cloud and precipitation microphysics would be derived using a combination of W-Band radar reflectivity profiles, microwave brightness temperatures, and shortwave reflectances in the near IR and visible bands. Such algorithms are beginning to emerge from A-Train analyses and show that this combination of measurements provides independent information regarding the cloud and precipitation microphysics from which process level information describing, for instance, autoconversion and accretion could be derived.

Attempting to derive simultaneous information about cloud and precipitation properties from a combination of remote sensors is exceedingly challenging. Essentially, it is possible to exploit the known responses of the various basic measurements to bimodal (cloud and precipitation) droplet modes (DSDs). The radar reflectivity (Z) responds to the sixth moment of the DSD. If precipitation is present in a particular volume, then Z characterizes the precipitation. However, if cloud droplets dominate the sixth moment then Z provides information regarding the cloud mode DSD. Solar reflectances, on the other hand, respond to the vertically integrated cross sectional area of the DSD. This typically means that the cloud droplet mode dominates the reflectances. The microwave brightness temperature, being primarily due to emission from the condensed water mass provides information on the vertically integrated third moment of the combined DSD. The unique challenge to algorithm developers is to untangle this information. What is important to understand, however, is that this specific combination of measurements is *required* as a minimal set to accomplish our science objectives. The algorithms and resulting science can be improved with additional information beyond the threshold set (by reducing uncertainty, as well as providing better connections to aerosol physical properties and boundary layer thermodynamic structure), however, loss of one of the required data streams would severely compromise our ability to accomplish this science objective.

The final geophysical parameter that we require is characterization of the aerosol profile properties. It has been well documented from modeling and observational studies over the last decade, that the aerosol field in the vicinity of shallow cumulus is quite complicated being a combination of primary aerosols such as sea salt and biogenics lofted from the ocean surface, secondary aerosols that have condensed from precursor gasses such as dimethylsufide, aerosols from natural and anthropogenic sources transported into the marine environment, and aerosols from all these sources that have been processed through earlier generations of clouds. *Coupling this complicated mixture of aerosol properties with variable thermodynamic and large-scale forcing explains the challenge our chosen Earth Science Target presents and the reason why it has resisted constraint using just passive remote sensing data.* The measurements needed to determine most directly aerosol geophysical parameters would be a combination of the lidar backscatter, extinction, and depolarization at 532 nm and lidar attenuated backscatter and depolarization at 1064 nm combined with reflectances from the stereo imager. Normal backscatter lidar measurements provide a single measurement that is a combination of backscatter and extinction that requires assumptions to disentangle. At 532 nm, we require both backscatter and extinction measured separately using the High Spectral Resolution Lidar (HSRL) technique. HSRL-derived backscatter and extinction at 532 nm would provide critical information that would allow the community to examine the nature of the aerosol spectrum in the vertical profiles close to broken cloud fields.

Quality of Measurements

The measurements we list as required are all incremental improvements over what was flown in the A-Train. The principle differences in the W-Band radar measurements over the CloudSat CPR is in higher vertical resolution (at least 250 m compared to 480 m), the spatial resolution (1 km versus 1.5 km), the sensitivity (-35 dBZe versus -28 dBZe), the addition of high precision Doppler velocity, and a capacity to measure much closer to the ocean surface (250 m versus 800 m). In addition, the 94 GHz microwave Tb provided by CloudSat was an afterthought while here we will engineer for this measurement from the start and therefore expect much higher accuracy and precision (2K uncertainty versus 5 K).

The Lidar measurements will be a significant advance over the lidar measurement provided by CALIPSO[15,16, 12]. Signal to noise in both channels will be much higher and vertical and horizontal resolution will be better. The addition of the HSRL technique at 532 nm will be a major advance that will allow us to characterize vertical profiles of aerosol properties with accuracy not possible from earlier generations of orbiting lidars. The horizontal and vertical resolution of the measurements will allow for profiling aerosols in partially cloud scenes right up to the edge of shallow convective clouds and marine stratocumulus.

The visible imager pair we include here will serve three purposes. First, stereo imagery will allow for characterization of the three-dimensional winds at the top of the cloudy boundary layer and the reflectances from clear pixels will assist the lidar measurements in retrieving aerosol property profiles. Second, the high resolution of the measurements will be beneficial in characterizing the cloud-scale motions but the near IR and visible channels will assist in the cloud property retrievals. And last, the imagery will also provide important information regarding the aerosol properties in a 50 km swath centered on the lidar and radar curtains.

Additional measurements that would significantly assist in the primary science target objective are listed in column 5 of Table 1. Note that a thorough assessment of the information content added to our threshold mission by these additional measurements is required and is beyond the scope of this document. These additional measurements could be provided by international partners, Venture class additions to a constellation, or other decadal survey or ancillary measurements with which we could collaborate either as part of a constellation or vicariously through conjunctions of opportunity. Briefly, these additional measurements could include the following:

a) Radar reflectivity measurements at Ka band in a 50 km cross track swath would map the spatial distribution of precipitation and be combined with the imager measurements and the W-Band radar measurements. In heavier precipitation in excess of 5 mm/hr, Ka band Z would add information to the retrieval of precipitation property profiles
b) Adding both backscatter and extinction at 355 nm would enable multiwavelength retrievals of aerosol properties such as effective radius and concentration and would provide much better inferences of CCN concentrations[12], and provide useful information about aerosol absorption. Backscatter measurements alone may provide more information regarding aerosol speciation.
c) Multiwavelength, multiangle polarimetric reflectances would allow for a significant advance in retrieving aerosol properties and could also assist in microphysical retrievals by helping identify the occurrence of the ice phase and constraining particle size at cloud top.
d) A microwave imager at standard channels ranging from 10 to 89 GHz would provide continuity across the scene and also provide temporal continuity to past measurements.
e) Measurements (visible, thermal IR, microwave sounding) from a geostationary orbit. The era of GOES-R type measurements (already being collected by Himawari-8) will allow us to know the temporal context of our retrieval targets from LEO orbits.
f) The addition of Oxygen A-band spectroscopic measurements would be very welcome as these data provide information regarding cloud depth and therefore cloud base. Knowledge of cloud base would significantly help retrievals of cloud base updraft and microphysical properties.

The ACE lidar-polarimeter measurement concept described in a related ACE response to this RFI#2 (Ferrare *et al.* 2016) would fulfill measurement requirements b) and c) above. We would also like to note that the technological advancements being realized by miniaturization represented by small- and cube-sat applications are extraordinarily exciting and will allow for many of the ancillary and even perhaps the threshold measurements (i.e. the imagers) to be realized at significantly lower cost compared to what was possible just a few years ago. We completely embrace such additions to the core measurements we list here.

Cross Cutting Issues

While Climate Variability and Change is the primary focus of this Earth Science target, we have also identified (in column 2, Q2 and Q3) questions that, while germane to our understanding of Climate Variability and Change, are also germane to other committee-defined earth science themes. For instance, shallow clouds systems are an important conduit for tropospheric pollutants to be vented into the free troposphere (Q2). As updrafts are accelerated through release of latent heat in shallow convection, boundary layer constituents are lofted into the free troposphere where these constituents are detrained and ultimately transported away from source regions. Additionally, the formation of precipitation in shallow convection is an important means for wet deposition of boundary layer pollutants and processing of pollutant aerosols.

Precipitation is a critical limiting factor in the growth of convection from shallow to deep modes and the interaction between cold pools produced by shallow convection and the ambient environment are important triggering mechanisms for further convection. Observing the dynamical properties of the updraft population and the cloud and precipitation microphysical properties that can be used to infer microphysical processes in warm shallow convection, therefore, is relevant to understanding the evolution of a field of convection as it evolves from shallow to deep and how the shallow convection in the vicinity of deep convection is being forced by the deeper clouds. Therefore, knowledge of warm shallow convection also has direct relevance to **Theme I: Global Hydrology and Water Resources** theme (Q3 in Table 1). As a matter of fact, characterizing the properties of the convective environment *prior* to initiation of deep convection allows for development of critical understanding of what mechanisms trigger the onset of deep convective modes. The onset of deep convection could be identified by monitoring GEO imagery.

We would also like to note several cross cutting applications that our core measurement suite would address. Since the threshold measurement suite represents an incremental advance over the existing measurements of the A-Train, much of the A-Train science can continue to be pursued but with increased precision with this suite. Several such applications would include the following:

Cirrus Clouds: While we have focused on boundary layer clouds and how their prediction in GCMs leads to model spread in climate sensitivity, tropical cirrus actually drive all models to predict a positive cloud feedback. As the climate warms, tropical cirrus maintain an approximately constant cloud top temperature and constant radiative forcing as the surface temperatures warm. While the models tend to agree, this aspect of the climate response to warming has not been confirmed observationally and it will be critically necessary going forward to monitor this fundamental aspect of the tropical climate response. The measurement suite we describe herein would build on the capacity of the A-Train to address this issue.

High Latitude Processes: Hydrological processes in the high latitudes winters are driven primarily by light snowfall that is adequately measured by Doppler radar at W-Band. The mixed phase cloud processes that typically produce snowfall at these latitudes would be characterized by the observational suite listed in Table 1. In particular, characterizing snow from shallow convective systems would benefit from the stereo imagery that we propose in Table 1. Additional possibilities for addressing mixed phase clouds and precipitation would be afforded by adding polarization to the imagers[13, 14].

Success Probability

The ACE mission in its pre-formulation phase has made significant progress regarding mission requirements and instrument technical readiness. ACE has and continues to leverage the advances in technical development and readiness of both instrument concepts (with NASA's Earth Science Technology Office [ESTO] support) and their related algorithm development (with ACE Pre-formulation Study support). The radar, lidar and polarimeter technology that comprises ACE's core measurement suite is expected to continue advancing to a technological readiness level that will permit this ACE component to go in full formulation phase by the time the 2017 Decadal Survey Report is published[10].

Instrument Readiness

The most significant radar advancements in the past 5 years relevant to ACE have been achieved under ESTO's IIP and ACT programs[21,22], with important contributions also by JPL and GSFC internal research and development funding, and the SBIR program[10]. This includes 1) Completion of the ACERAD[18] concept (PI: S. Durden, JPL) technology maturation through the IIP'08 funding, 2) development of the WiSCR[19] and 3CPR[20] instrument concept through IIP'10 (PI: P. Racette) and IIP'13 (PI: L. Li) and 3) of the 3CPR instrument concept IIP'13 (PI: G. Sadowy). With continued or expanded ESTO investments it is likely that most (if not all) of the BM measurements will be ready for space well within the next 10 years. Lidar readiness is addressed in detail in references 15 and 16.

Algorithm Readiness

Starting in FY13, ACE has increasingly prioritized investments in risk reduction, specifically via algorithm development and the data acquisition and analyses to support that activity. Furthermore, the ACE Pre-formulation Study currently supports a robust multi-sensor algorithm development activity in the cloud science area[10] and progress is also being made in lidar algorithm develoment[12]. Over the past several years ACE has invested considerably in creation of data sets that can form the foundation for aerosol, cloud, and precipitation retrieval algorithm development. ACE has formed a strong collaboration with the GPM ground validation team and participated in two of their activities in what has been termed the ACE Radar Definition Experiments (RADEX). Both of these campaigns featured multi frequency airborne Doppler radars on the ER2 and both of these campaigns included coordinated in situ aircraft sampling. Together, these data sets are a critical investment in the development of algorithms for the ACE era of multifrequency radar. Thus, while much progress is being made, more remains to be done and continued investments in algorithm development needs to go hand-and-and-hand with instrument preparations.

Affordability

Our emphasis in this document has been (Table 1) to articulate both a core suite of measurements (i.e. a minimum set) and a baseline suite (i.e. the measurements that would maximize information in this complicated multi dimensional problem). In the core suite of measurements, our emphasis is strictly on affordability and a bare-bones mission. However, based on experience with the A-Train, we can be reasonably certain that once planning for this baseline is established, additional assets will be committed when other partners see the benefit of synergy.

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Theme	Earth Science Target Focused Science Questions	Geophysical Parameters	Measurements
<u>Climate Sensitivity</u> Estimates of the earth's climate sensitivity to doubled CO_2 ranges between 1.5 and 5° C. This range is due to many sources of uncertainty. However, it is well understood that a dominant source of uncertainty is differences in simulated marine boundary layer clouds – a cloud regime that covers nearly 2/3 of the earth's surface at any instant. Our Quantitative Value Framework objective is to reduce the climate sensitivity uncertainty by 25% by improving our theoretical understanding of MBL cloud systems.	<u>Q1. Climate Variability and Change</u> How will shortwave cloud forcing change as the climate warms due to changes in MBL clouds? • What is the specific role of aerosol in modulating the macroscale and microphysical properties of boundary layer clouds and the planetary albedo under a changing climate? • What role does the seasonal cycle of middle and high latitude cloud radiative forcing play in the poleward transport of heat and how is this radiative forcing partitioned as functions of cloud genre? • For a given thermodynamic and large-scale forcing, what is the interaction between cloud-scale dynamics and cloud-precipitation processes (i.e. autoconversion and accretion) as a function of natural and anthropogenic aerosol?	GP1. Hydrometeor Layer Detection GP2. Cloud-Scale Vertical and Horizontal Air Motions GP3. Simultaneously occurring Cloud and precipitation microphysical property profiles (Water Content, particle size, and number concentration) GP4. Profiles of Aerosol Properties that provide information on CCN concentrations	<u>Threshold Measurements</u> TM1. Nadir W-band Radar Reflectivity and Doppler Velocity, microwave Tb • Horizontal Resolution: 1 km • Vertical Resolution: 250 m • Min Detection: -35 dBZ • Tb accuracy 2 Kelvins TM2. Aerosol Backscatter and depolarization at 532 and 1064 nm and aerosol extinction at 532 nm. • Horizontal Resolution: 100 m • Vertical Resolution: 50 m TM3. Narrow Swath Stereo Imager Pair (visible and near Infrared) • Horizontal Resolution: 50 m <u>Baseline Measurements</u> *BM1. Ka-bands Scanning Radar Reflectivity, microwave Tb (primarily for heavier precipitation)* *BM2.* Aerosol extinction and Backscatter at 355 nm, *BM3. High Resolution Narrow Swath VNIR-SWIR Polarimetric reflectances* *BM4. Microwave Tb imager* *BM5. Visible and IR GOES R-like measurements with high time resolution.* *BM6. Oxygen A band spectrometery*
	<u>Cross Cutting Earth Science Targets</u>		
	<u>Q2. Weather: Atmospheric Dynamics and Thermodynamics</u> How do cloudy boundary layers respond to variable Aerosol as a function of large scale forcing? • At what rate are boundary layer constituents vented to the free troposphere as a function of large-scale and local forcing and aerosol background?		
	<u>Q3. Global Hydrology and Water Resources</u> What is the role of aerosol-modulated cloud processes in snow and rain production in boundary layer cloud systems that are developing into deep convective systems? • To what degrees do various microphysical processes when coupled with large-scale dynamics and variable aerosol modulate precipitation production within shallow cumulus systems that are developing into deep convection? • What is the spectrum of cloud-scale updraft velocities as a function of background aerosol vertical profiles and large-scale forcing in shallow cumulus fields that are in the process of deepening into precipitating cloud systems? • What is the role of cold pools and outflow boundaries in triggering new convection?		

Table 1: ACE Aerosol-Cloud Science Traceability Matrix. In order to solve the MCFU problem and reduce the uncertainty in climate sensitivity by 25%, we must improve our fundamental understanding of the physical processes that cause MBL clouds to increase or decrease as the climate warms. Our measurement concept in response to the 2017 Decadal Survey committee's request is summarized in Table 1 where we elaborate on this overarching theme with a set of specific science questions that are listed in each sub-theme headings (column 2). A necessary requirement to provide observational constraints to these questions is that a comprehensive quantitative description of the state of the system must be had. The geophysical variables that would sufficiently describe the physical state of the system are listed in column 3 of Table 1. Following the committee's request, we then list a set of measurements and requirements on those measurements from which the geophysical variables could be retrieved in column 4 of table 1. At its essence, Table 1 is a notional Science Traceability Matrix where the overarching scientific themes scope ultimately to the set of measurements needed to address science questions.