Low Clouds: Drivers of Climate Sensitivity and Variability

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October 30, 2015

This white paper focuses on low-level clouds, their coupling with boundary layer dynamics and thermodynamics, and their role in cloud feedbacks. Given the importance of low clouds to climate, we urge the Decadal Survey to endorse a strong, dedicated effort to continue satellite-based observations of low clouds using current techniques, and to develop and improve upon existing capabilities.

Cloud-aerosol interactions are addressed in other white papers. The improvements to satellite observations of low clouds and boundary layer structure described below would also be valuable in addressing those issues.

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 recent National Academy of Sciences report “Continuity of NASA Earth Observations from Space: A Value Framework” recommends that reduction of the uncertainty in equilibrium climate sensitivity should be a NASA priority. Shallow clouds (cumulus, stratocumulus, stratus) are the greatest source of spread in model estimates of climate sensitivity and thus uncertainty in the magnitude of future climate change. Several recent lines of evidence suggest that low clouds will enhance climate warming, but uncertainty about low cloud response to climate change, including coupling to the global circulation, remains large.

Underestimates of Southern Ocean low clouds in climate models have global and regional significance, affecting global and inter-hemispheric energy balance (likely connected to the common model error of having a double Intertropical Convergence Zone). Mixed-phase low cloud behavior varies widely among models because of inadequate understanding of the physics controlling partitioning of liquid and ice, which have different radiative properties. This introduces uncertainty into projections of Arctic sea ice decline. Interactions between climate changes in high-latitude low clouds, sea ice changes, and weather have been proposed but are poorly constrained.

Errors in the simulated transition from shallow to deep convection are thought to explain the inability of models to simulate features of climate variability that involve the organization of deep convection on large scales (MJO, monsoons), as well as model biases in the diurnal cycle of continental precipitation.

For these reasons low clouds are central to three of the four guiding questions of the WCRP Grand Challenge on Clouds, Circulation, and Climate Sensitivity: (1) What role does convection play in cloud feedback? (2) What controls the position, strength, and variability of the tropical rain belts? (3) What role does convective aggregation play in climate?

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

Satellite data records are now approaching the length needed to detect regional secular trends as the signal from climate change emerges from natural variability. Immediate focused observations are needed to determine whether the predicted decline in low clouds as the climate warms, and their enhancement of greenhouse gas warming, is realistic. Existing technology can accomplish this with reasonable investments, and research missions optimized to observe low clouds can be combined with operational weather satellites to produce comprehensive spatial-temporal sampling.

Longer records will also allow more precise determination of the sensitivity of low clouds to environmental parameters from natural climate variability, leading to reduced uncertainty in prediction of how low clouds feedback on greenhouse warming.

Future observations would benefit from almost a decade's experiences with the A-Train and ground-based "supersites," especially the maturation of observational strategies using information from multiple sensors to determine vertically-resolved macro- and micro-physical information.

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

Low cloud feedbacks occur primarily over broad regions of the ocean where *in situ* and surface remote sensing observations are sparse or absent. Even over land, many climatically sensitive regions (e.g., Amazonia, Africa) have little or no routine local cloud observations.

Modes of climatic variability affected by low clouds (e.g., MJO) have their genesis over remote ocean areas and must be observed as planetary-scale phenomena to be understood. Global coverage by satellites is required to monitor dynamically-induced shifts in low cloud patterns.

Please focus on the role of space-based observations and comment on:

a. Whether existing and planned U.S. and international programs will provide the capabilities necessary to make substantial progress on the identified challenge and associated questions. If not, what additional investments are needed?

The A-Train constellation has had a tremendous impact on understanding of low clouds and their role in climate, in particular on drizzle formation and instantaneous cloud forcing. However, A-Train instruments are nearing end-of-life and urgently need to be replaced and nominally upgraded to provide continuity with current data, better detect clouds near the surface, reduce uncertainties in retrieved low cloud properties, and provide better information about the environment in which low clouds are embedded.

Mixed-phase clouds in particular remain challenging and likely require a new focus on 3D observing systems. Active instruments combined with passive microwave, visible, and infrared are key. The planned ESA EarthCare mission will provide some degree of cloud radar data continuity, but with no passive microwave, very limited VIS/NIR information, and a short mission life (owing in part to a low earth orbit and increased atmospheric drag relative to the A-Train).

Challenges are especially acute in capturing atmospheric dynamics from satellites. Meteorological (re-)analyses informed by passive microwave and infrared sounders are currently the only source of global large-scale information but winds and water vapor in and near the boundary layer, which are central to the behavior of low clouds, are highly uncertain over remote regions. Better estimates of surface turbulent fluxes, partly constrained by satellite measurements of winds, are also needed. Better knowledge of dynamical fields would allow for deeper understanding of the development and persistence of marine stratocumulus, the transition from stratocumulus to trade cumulus, and the presence or absence of drizzle and light rain. The planned ESA ADM-Aeolus mission will provide a first taste of the value of such measurements.

Therefore, in addition to maintaining passive microwave and cloud lidar capabilities, we strongly recommend continuation of the A-Train with:

1. Millimeter cloud radar with higher vertical resolution than CloudSat to better detect near-surface clouds and precipitation, and capture shallow cloud vertical structure. Scanning over even a narrow swath would greatly reduce CloudSat sampling limitations that restrict it to primarily statistical studies.

2. Multichannel vis-IR imager(s) with 100 m or better spatial resolution and nominal multi-angle polarization capability. Increased resolution will reduce the partial coverage of low clouds in a large fraction of pixels with current sensors, which currently limits our ability to confidently determine cloud fraction, optical depth, and particle size distributions. Multi-angle polarization imagers could use stereo techniques to derive accurate cloud top heights. Polarization angular dependence provides cloud top particle size and thermodynamic phase along with aerosol properties.

3. The existing Landsat-8 OLI/TIRS sensors provide high-resolution imaging of maritime low clouds near islands and coasts, as will the planned Landsat-9. These data are presently under-utilized for low clouds and a broader strategy for Landsat-10 should be considered.

4. In the longer term, emerging technologies such as Doppler radar and wind lidar, water vapor differential absorption (DIAL) or Raman lidar can advance understanding of PBL dynamics and thermodynamic structure that determine the type and spatial extent of low clouds. Routine, less expensive time lapse (stereo) imaging (from cubesats) may also prove effective.

We recommend a strong suborbital program to advance these technologies for eventual use in space-borne observations of low clouds.

b. How to link space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs

Surface-based remote sensing (e.g., ARM facilities) could be better utilized to complement satellite data (continuous point data vs. global data with long repeat time) and validate satellite algorithms.

Geostationary data can be better exploited to provide a global temporal context for snapshot low Earth orbit observations.

Satellite data combined with reanalysis fields of non-observed parameters will optimize science impact. More data products should be assimilated into models and state-of-the-art assimilation techniques adopted in the U.S.

c. The anticipated scientific and societal benefits

Assessing future climate impacts requires knowing how much we expect the climate to change for a given forcing. Low clouds determine this response to a greater extent than any other part of the climate system, and improvement in this area is a high priority.

Interactions between shallow and deep clouds affect weather prediction on many time scales. Predicting tropical rainy period onset will benefit from increased medium-range predictability to be gained by better simulation of intraseasonal variability. Correct daily timing of continental precipitation may allow for better projections of soil moisture anomalies in a warming climate. Circulation responses to changing patterns of low clouds may change weather patterns and rainfall distributions.

d. The science communities that would be involved.

A commitment to enhanced observations of low clouds will influence the priorities of WCRP and GEWEX and have an impact on IPCC assessments. The remote sensing, cloud-scale modeling, climate modeling, tropical meteorology, numerical weather prediction, and climate impacts communities would all participate in designing and implementing an observational strategy, learning from the observations, and transferring knowledge to improve models and have more confidence in the impacts they predict.