Clouds, Water Vapor, and Climate Sensitivity

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The range of climate sensitivity estimates from global climate models has hardly changed since the Charney report of 1979. The dominant source of uncertainty has been traced to model diversity in the response of clouds to climate change. Narrowing the uncertainty in climate sensitivity and improving the confidence of climate projections represents one of the greatest challenges faced by the Earth Science community, suggesting better constraints on the magnitude of cloud feedbacks are key. In organizing the Grand Challenge Initiative on Clouds, Circulation, and Climate Sensitivity (Bony et al. 2015), the WCRP has recognized the critical importance of advancing our understanding of cloud feedbacks and the processes responsible for them.

While we have had little success in reducing the range of estimated climate sensitivity, we have greatly improved our knowledge of the processes involved. Fundamental mechanisms behind longwave feedbacks due to deep tropical clouds are better understood (Hartmann and Larson, 2002), although questions remain about the importance of mesoscale organizing processes (Wing and Emanuel, 2014; Mauritsen and Stevens, 2015). The dominant uncertainty in cloud feedback, however, is associated with shallow marine clouds (Bony and Dufresne, 2005), which are highly sensitive to changes in their environment. A number of verifiable mechanisms underlying these feedbacks have recently been proposed (Brient and Bony, 2013; Sherwood et al., 2014; Nuijens et al 2015) which require testing against observations.

Accumulating evidence suggests the relevant shallow cloud processes are mediated more by atmospheric circulations than by microphysical processes. Both theoretical arguments and modeling across scales suggest that many aspects of circulation – the depth of the marine boundary layer, the moisture gradient between the sea surface and the free troposphere, the rate of subsidence, etc. – will change in response to global warming. It is these changes, many involving the redistribution of water vapor in the vertical, that are expected to have by far the largest impact on shallow clouds in a future climate. The large diversity in predicted cloud feedbacks is due to the net feedback being the result of a balance of processes which are poorly represented in global models.

Cloud radiative feedbacks are the result of changes in cloud amount, height, albedo, and thermodynamic phase. The predicted forced changes in these properties are small but radiatively significant and the signatures will only emerge from the noise of natural variability on multi-decade timescales, placing very stringent requirements on the long term accuracy and stability of the sensors used to detect such change. The most easily observed signatures of the cloud response are expected to appear as changes in vertical structure rather than vertically-integrated quantities (Chepfer et al 2015).

Progress since the first Decadal Survey

CALIPSO and CloudSat entered the A-Train just before the release of the first Decadal Survey report. We are now approaching a decade of cloud profiling from lidar and radar, co-located with radiance measurements from CERES and MODIS. It is hard to overstate the value of these observations in refining our understanding (L'Ecuyer and Jiang, 2011). Active profiling has provided, for example, direct measurement of cloud vertical structure in place of ambiguous retrievals based on top-of-atmosphere radiances (Mace and Wrenn, 2013; Di Michele, et al. 2013). Comparisons of the vertical distribution of shallow clouds observed by lidar with model predictions has shown that global models poorly represent the influence of the large-scale environment on cloud structure (Nam et al. 2012). Co-location of active profiles with broadband fluxes from CERES has significantly reduced uncertainties in the surface radiation budget and enabled calculation of atmospheric heating profiles (Haynes et al. 2013), revolutionizing our ability to understand the coupling of clouds and circulation.

Detection of the changes in cloud properties responsible for feedbacks, on the multi-decadal scales required for climate change signals to emerge from the noise of natural variability, requires an observing system with exceptional stability. Lidar, via time-of-flight measurements of vertical cloud structure, provides the most rigorous observation of cloud fraction and cloud height (thought to be the cloud variables most responsible for shortwave and longwave cloud feedbacks, respectively). Nadir-viewing lidar has been shown to be capable of providing an accurate climate benchmark of 3D cloud distribution, with sampling uncertainty below that of the natural variability of clouds at space-time scales relevant to climate (global monthly and annual zonal mean, for example). With addition of co-located, well-calibrated passive sensors, cloud albedo and diabatic heating can also be constrained.

Why are space-based observations fundamental?

Clouds and radiation are highly variable in space and time and many of the most important feedbacks occur over remote ocean regions. Global, unbiased space-time sampling from satellite sensors is required to provide the necessary constraints on global feedbacks.

Measurement needs vs. planned programs.

Active cloud profiling: We have reaped untold benefits from 35-plus years of observations from passive satellite sensors. A similar multi-decade record of combined active-passive observations will provide additional benefits, but only if future missions are designed in a way which supports the construction of consistent, long term unbiased data records as one of their objectives. EarthCARE will launch in the near term, but plans must be developed now for the post-EarthCARE era. The Aerosol-Clouds-Ecosystems (ACE) mission, identified by the first Decadal Survey report but still in pre-formulation phase, includes advanced lidar and cloud radar instruments. ACE is currently envisioned as a mission focused on process studies rather than producing climate data records, however, and the core payload does not include the sensors necessary to address the issues discussed above.

Water vapor: Shallow marine clouds are highly sensitive to the modulation of longwave cooling by water vapor in the lower free troposphere, and to the detailed vertical distribution of water vapor in the lowest 2 km of the atmosphere. We are limited by the capabilities of current satellite retrievals in testing hypotheses and constraining critical processes. High spectral resolution measurements in the thermal infrared and multi-channel microwave radiances from AIRS/AMSU represent the current state of the art, but the broad radiative kernel functions are unable to resolve either the shallow marine boundary layer or the gradients in water which are critical to shallow cloud processes.

No satellite missions are planned which could overcome these limitations. Advanced radio occultation constellations optimized for water vapor retrievals may help, but they inherently suffer from poor horizontal resolution. Water vapor DIAL lidar can in principle provide the vertically resolved profiles necessary to characterize the vertical distribution of water vapor. Although DIAL technology is not yet sufficiently mature for satellite applications, a new generation of aircraft instruments is now coming on line. Appropriate technology developments in the near term would set the stage for a transition to space in the near future. There may also be a role for networks of ground-based instruments which could be deployed in regions of particular interest or in regions not viewable from satellite, such as the humidity field beneath opaque clouds.

Anticipated societal benefits

Reducing uncertainties in climate sensitivity will improve our abilities to predict climate change, which would have a huge economic value (Cooke et al. 2013). The resulting improved understanding of cloud processes will also very likely have benefits for numerical weather prediction. Advances in understanding and increased confidence in climate predictions will improve our abilities to plan for and mitigate the impacts of climate change, with tremendous societal benefits.

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