Observational opportunities for addressing the Grand Science Challenge on Clouds, Circulation and Climate Sensitivity

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Backdrop

A few years ago the World Climate Research Programme initiated a Grand Science Challenge initiative, targeting "highly specific and highly focused [topics] identifying a specific barrier preventing progress in a critical area of climate science." These initiatives are intended to stimulate the public imagination, and to be actionable potentially transformative.

In this white paper we discuss observations that are important to the Grand Science Challenge on Clouds, Circulation and Climate Sensitivity based on activities undertaken so far. These include extensive community consultation and ten expert workshops in the US and Europe dedicated to better articulating the key challenges and to outlining and initiating a program of coordinated research around them. Through this process we identified four specific questions that stand out "both because of their centrality to a more specific understanding of global and regional climate changes, and because new and emerging approaches or insights are . . . making them more tractable" (Bony et al. 2015, doi:10.1038/ngeo2398) These questions are:

- What role does convection play in cloud feedbacks?
- What controls the position, strength and variability of the storm tracks?
- What controls the position, strength and variability of the tropical rain bands?
- What role does convective aggregation play in climate?

Answers to these questions are essential for assessing the magnitude of global changes (climate sensitivity) and advancing predictions of regional climate changes. The former is important for mitigating against climate change, the latter central to adaptation measures.

Key Science Needs

We believe new observations are important for progress on three important issues:

Radiative coupling between clouds and circulation Cloud radiative effects profoundly influence the atmospheric circulation in both the tropics and extra-tropics across a large range of temporal and spatial scales. Cloud radiative effects have a strong influence on the strength of extra-tropical storms and influence storm-track position and its sensitivity to perturbations. Similarly the position, strength and structure of tropical rain bands, including circulation systems such as the Madden Julian Oscillation (MJO), El Nino-Southern Oscillation (ENSO) and even the amplitude of decadal variability, are highly sensitive to how clouds interact with circulation through their radiative effects. New approaches to synthesizing observations have demonstrated the possibility of constraining the atmospheric heat budget through a combination of well-calibrated, top-of-the-atmosphere irradiance measurements (e.g. from CERES) and atmospheric profiling of clouds (e.g. from CloudSat and Calipso). *To constrain atmospheric energy and water budgets sufficiently to understand links between clouds and circulations, top-of-atmosphere measurements must be available at high sampling rates and must be augmented by estimates of surface turbulent heat and radiation fluxes.*

Convective Aggregation Idealized modeling studies suggest that convection tends to spontaneously aggregate, leading to larger convective systems and systematically drier conditions outside the convective regions, with direct impacts for the top-of-atmosphere energy budget. This phenomenon is thought to be important to a variety of real-world phenomena including tropical storms, the MJO, and tropical rain bands (the monsoon, over land). Because the tendency to self-aggregate increases with temperature this mechanism may also affect Earth's climate sensitivity. Current understanding of convective aggregation suggests an important role for low-level divergent circulations and the distribution of water vapor, both of which are quite poorly measured at present. *An ability to measure profiles of water vapor in the lower troposphere and the profile of divergence throughout the troposphere is necessary to test current ideas about the mechanisms driving convective aggregation and the resulting impacts on climate.*

Convection and Cloud Feedbacks The understanding of processes controlling cloud feedbacks, and hence Earth's equilibrium climate sensitivity, have become increasingly precise over the past years. Ideas have become sufficiently specific to encourage experimental and observational approaches for constraining the magnitude of such feedbacks. Here again the key questions are also related to the interplay of winds and water vapor. As one example lower tropospheric mixing, both as a result of convective processes and time-averaged large-scale circulation, scales strongly with feedbacks in models but is poorly constrained by observations. Proxies for small- and large-scale mixing are given by the structure and depth of the moist layer over the tropical oceans. *For this question, too, constraining water vapor anomalies in the lower tropospheres and the vertical profile of divergent circulation would constitute a tremendous advance.*

Specific Measurements

Our comments below reflect the experience that, for climate and process purposes, it is not always necessary to achieve high precision at the time and space scale of the process since one can often aggregate data in a way that allows for testing process hypotheses over a large ensemble of process realizations. Successful recent examples include the compositing of observations around features of interest, including mid-latitude cyclones and the MJO, and the effectiveness of temporal and spatial averaging in answering process questions. Thus absolute accuracy and independence of errors may be more valuable than precision.

Lower Tropospheric Relative Humidity Water vapor in the lower troposphere is highly variable in space. Current observational estimates rely mainly on passive measurement of spectrally-resolved microwave and infrared radiances at the top of the atmosphere but such radiances are not very sensitive to water vapor near the surface. The resulting retrievals appear skillful, at least in clear skies, because they are well correlated with *in situ* observations, but this does not reflect true skill: passive measurements are primarily sensitive to relative humidity above the inversion and/or surface temperature, both of which are themselves highly correlated with lower tropospheric water vapor mixing ratio. This apparent skill is not sufficient because key scientific needs — including surface fluxes and impacts on cloud formation — depend on the small *departures* from these statistical relationships and so require accurate estimates of *relative humidity* and/or its vertical gradient at low levels. We also need these data underneath and around clouds which may require high spatial resolution sounders or active (e.g. lidar) methods.

3-D Wind profiling The planned ESA ADM-Aeolus mission (Doppler wind lidar) is an dramatic step forward in atmospheric wind profiling. The mission is purely experimental, however, and will a single component of the wind over a limited lifetime in a unique orbit, restricting the ability to use the observations in conjunction with others. Advanced 3-D global wind profiling would be a genuine revolution for process understanding, weather prediction, and climate science. Observing system simulations suggest that it could substantially improve the initialization of numerical weather prediction models. This is especially true in the tropics where wind is poorly constrained by temperature observations, but is also relevant at sub-synoptic scales in the extra-tropics which would help in predicting extreme wind storms. Co-located measurements of atmospheric winds, clouds and latent and radiative heating could also greatly advance understanding of atmospheric convection—still the Achilles heel of atmospheric modeling. Even the time-averaged tropical overturning circulation is not accurately known and varies substantially between models are reanalyses. Pursuing space-borne measurements of atmospheric winds, using active and passive (microwave) systems, is a high-risk endeavor but one with the potential for extraordinary gains.

Atmospheric Energy Budget Nearly a decade of observation by satellite-borne active sensors (profiling radars and lidars) have transformed our understanding of the vertical distribution of condensate (especially cloud ice) and aerosols. These measurements, especially when used to inform calibrated irradiance measurements at the top of the atmosphere, are often taken for granted but they are central to advancing understanding of the atmospheric heat budget and the coupling of clouds to circulation. The only mission planned to follow up on the A-Train's success is ESA's EarthCARE, but the likely short mission life and less capable instrument suite, relative to the A-Train, emphasizes the need to develop a comprehensive plan for the post-EarthCARE period. Understanding of the climate system, and especially the ability to detect changes in the vertical distribution of clouds to test ideas about cloud feedbacks, depends very much on our ability to maintain over the long term the types of measurements that the combination of CERES, CloudSat and Calipso provide. More precise and accurate measurements of the radiation budget at TOA, for instance through CLARREO-like approaches, would allow for independent measurements of ocean heat uptake and provide valuable new constraints on understanding of climate change and fluctuations at decadal timescales.

Expected Impacts and Involved Communities

The measurement program articulated above could substantially reduce uncertainty in estimates of Earth's equilbrium climate sensitivity particularly at the high end where the risks are greatest the economic benefits of better information are largest. Observations of atmospheric heating derived from sustained observations of cloud profiles and top-of-atmosphere irradiance would better constrain understanding of processes responsible for the large-scale structure of atmospheric circulations systems, like the jets, storm-tracks and rain bands, thereby laying the foundation for understanding regional climate changes and adaptive strategies. Because atmospheric circulation affects every aspect of the climate system on all timescales, these measurements would greatly influence every aspect of Earth System Science, including attempts to understand the role of biospheric and cryospheric processes.