High Resolution Profiling by Radio Occultation:
The Missing Element for Climate and Weather Prediction & Monitoring

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Significantly better understanding of the water and energy cycles and associated feedbacks is required to reduce uncertainty about future climate globally and regionally. Our primary recommendation is to add dense, active, very high vertical resolution, precision and accuracy water and temperature profiling via radio occultation to complement existing observations of clouds, precipitation and energy fluxes in order to tie the entire weather and climate system together. This will also dramatically improve the realism and utility of global analyses for climate as well as forecasting (increasingly extreme) weather.

Earth's atmosphere is a radiative convective heat engine continually working to balance absorbed solar radiation by transporting near-surface latent heat upward and poleward to regions of lower opacity that radiate the energy to space via IR. The system's complexity lies in the intimate coupling and interplay between water vapor, temperature, stability, wind, turbulence, clouds, aerosols, evaporation, precipitation, albedo, opacity, OLR and convective and advective fluxes. Accurate prediction of climate therefore requires an understanding of this coupled behavior and its proper representation in models.

Our understanding continues to grow both in terms of what we know and what we don't. Particularly troubling are the large uncertainties in the surface energy balance[1]. Improving upon this requires globally distributed high vertical resolution measurements that constrain SW and LW radiation and turbulent fluxes in the lowermost troposphere, a tall order. The measured albedos of the two hemispheres are nearly identical with little interannual variability, features not reproduced in models[2]. Most climate feedbacks are tied to water such that an accurate water cycle is needed to get the feedbacks correct. The biggest spread in model climate sensitivity is associated with the cloud feedback. Approximately half of the variance in climate models is associated with boundary layer clouds[3]. Researchers have noted the importance of understanding the coupling between the clouds and the large scale circulation[4 5].

Recent results suggest that models with higher climate sensitivity are more realistic[3 5 6]. Sherwood et al[3] found that tropical boundary layer (BL) cloudiness in climate models decreases as climate warms, apparently due to enhanced mixing between the BL and free troposphere that dries out the BL and increases SW absorption. The more "realistic" models (defined as being more similar to re-analyses) predict larger reductions in cloudiness, implying warming will be relatively severe. However, re-analyses are suspect because of the lack of dense, vertically resolved observations near the Tropical BL top to constrain them, thus undermining the final step of logic in concluding warming will be relatively severe. In fact, comparison with GPS derived moisture results indicates all models and analyses have signatures of too much mixing just above the tropical BL top[7]. This underscores the **need for significantly better analyses** discussed below.

UT humidity is critical as well, as it directly affects water vapor and UT cloud feedbacks there. Descending low mixing ratio air from the UT is key to the subtropical "radiator fins" of the climate system[8]. This dry descending air also dries the BL as it is entrained there. Climate models tend to underestimate the zonal mean dryness[6], due perhaps to too much mixing in the models[7]. There is also a significant spread in Hadley cell representation in models which is correlated with cloud variations[6]. This underscores the point that understanding the moisture distribution and clouds requires understanding the circulation, vertical velocity and divergence profile which is tied to the radiative cooling profile and the vertical stability of the atmosphere. Overall the overturning circulation should slow down globally[9] but there will be regional variations[5] that will also likely change the stability as well.

Moreover, models predict increasingly extreme weather resulting in floods and droughts[10] that must be predicted on weather and climate time scales. These aspects are of particular importance in areas where society is more vulnerable to variability and change.

Observational needs

Reducing uncertainty requires better understanding of the global water and energy cycles. Process-based constraints on feedbacks are likely to be key to reducing the uncertainty in future projections[6]. Observations must provide information with sufficient process-constraining detail (resolution and precision) throughout the troposphere to isolate and characterize the key coupled processes and tie them to the energy budget. The key variables are relative and specific humidity, temperature, clouds, precipitation, horizontal and vertical winds and their divergence, turbulent mixing and fluxes, atmospheric stability, and radiation.

At present, CERES measures short and long wave TOA fluxes and Cloudsat and Calipso profile clouds and aerosols which need to continue. Soon Aeolus will measure winds. A key missing global observational element is comparable very high vertical resolution water vapor and temperature profiling. Satellite radiances are too blunt vertically to characterize the scales at which water vapor and temperature vary, just as they are for clouds (which necessitated the Cloudsat and Calipso missions). To further reinforce this point, radiosondes continue to be critical to field campaigns and have very large impact on weather forecasts, despite their sparse sampling and the enormous volume of global radiance data.

RO Solution

The solution to this missing observational element is satellite to satellite radio occultation (RO). RO comes in two flavors: (1) GNSS RO near 1.5 GHz and (2) occultations near the 22 and 183 GHz water absorption lines referred to as the Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS). Both systems profile the atmosphere with 100-200 m vertical resolution and corresponding ~70-100 km horizontal resolution[11] with high precision, accuracy (via inherent self-calibration) and all-weather global coverage. GNSS RO uses transmitters already in orbit such that only the receivers need to be flown. ATOMMS requires its own orbiting transmitters and receivers. Cubesat technology now makes this a cost effective option as noted below.

ATOMMS was conceived because GNSS RO cannot simultaneously profile temperature and water vapor and has little sensitivity to water vapor in the UT, the winter hemisphere and stratosphere. ATOMMS RO is designed to address the numerous climate needs described above. It will simultaneously profile water vapor and temperature with 1-3% and 0.4K precisions respectively and still better accuracy, from near the surface to the mesopause[12,13], enabling radiosonde-like profiling including atmospheric stability from orbit but with much better accuracy. ATOMMS both sees clouds and sees through them via a doubly differential absorption approach [12,13]. NSF funded surface experiments using a prototype ATOMMS instrument demonstrated unambiguous 1% water vapor retrievals in clear, clouds and rainy conditions up to an optical depth of 17 [14,15].

While the utility of RO has been questioned due to its horizontal resolution, we note that in the tropical free troposphere, GNSS RO actually observes higher percentages of both extremely high and extremely low humidity than climate models, AIRS and all but one of the global analyses[7]. Clearly, very high vertical resolution, precision and all-weather sampling are important to observing water.

The utility and need for ATOMMS are demonstrated with a polar example. Reducing the wide scatter of model predicted rates of shrinking sea ice requires reducing uncertainties in the surface energy budget. In-situ observations in this remote region are extremely sparse and satellite radiances provide limited constraints because of poor vertical resolution, sensitivity to variable surface conditions, low clouds and thermal inversions. Sondes and the SHEBA field campaign[16] reveal a complex, near-surface environment with frequent low clouds just a few hundred meters above the surface, often containing super cooled water, large variations in stability and turbulent mixing and interaction with overlying warmer, moister air that maintains the clouds. ATOMMS 100m resolution profiles of temperature, stability, water vapor, cloud opacity and liquid water and turbulence (via scintillations = "twinkling of a star") in the lowermost troposphere across the remote polar regions would provide constraints urgently needed to understand and model the surface energy budget, clouds and surface ice and reduce uncertainty in an increasingly warmer climate. Development of an ATOMMS capability was recommended by the ECMWF-THORPEX Polar Workshop[17].

Synergy exploitation

Synergistic developments in observational needs, RO capabilities and cubesat technology present us with a remarkable opportunity to make quantum improvements in our knowledge and predictive skill. To summarize,

- Precise, much higher vertical information on water vapor, temperature and dynamics is needed globally to reduce climate uncertainty, monitor climate change and improve weather forecasts.
- Satellite to satellite RO provides very high vertical resolution, precision and information content but its sampling to date has been sparse (GNSS RO: 2000 occ/day; ATOMMS: 0 occ/day).
- Much higher densities of occultations would capture the range of behavior over increasingly smaller regions and shorter time scales to more fully characterize and understand regional and global climate behavior and underlying processes.
- Very large numbers of occultations will also have large impact on the analyses. Assimilating 128,000 GNSS occultations per day reduces errors in ECWMF mid-tropospheric water vapor analyses in warm areas by ~50% [18] [19] implying approximately 2/3 of the analysis humidity information comes from the RO. The estimated impact of 128,000 occultations on ECMWF winds[17] [18] exceeds that estimated for Aeolus[20] except very close to the surface.
- In present analyses, ~80% of the information comes from the forecast and the rest from the assimilated observations[21]. Assimilating very large numbers of precise RO information will greatly increase the percentage of observational information contained in the analyses (simultaneously reducing the model contribution), yielding analyses far better suited for climate research.
- Assimilating very large numbers of occultations will force the analyses to get the water right while simultaneously exposing systematic model errors in so-called "fast" processes whenever the model climatology disagrees with observational reality. The knowledge gained from this will result in improved realism of both NWP and climate models and their forecasting skill.
- Better analyses means better initial conditions for better weather forecasts.

Miniaturization => low cost satellite constellations

The dramatic increase in RO sampling densities needed is readily achievable at relatively low cost via instrument miniaturization and cubesat technology. A GPS RO receiver-spacecraft design now exists that can provide the COSMIC2 level of performance and 2.5 times the number of occultations in a spacecraft approximate 30 times smaller than the COSMIC2 spacecraft. The 3rd generation design of the ATOMMS transmitter-receiver instrument enables GNSS RO and ATOMMS instruments to fit in a 12U (~20 x 20 x 30 cm) spacecraft.

Therefore, we propose an ATOMMS RO constellation as the right tool to provide the urgently needed precise, self-calibrated, high vertical resolution information about the gas phase to complement CERES, Cloudsat, Calipso and Aeolus observations and predict and monitor the evolution of the Earth's climate. As an example, a 60 satellite constellation would provide approximately 25,000 ATOMMS and 170,000 GNSS RO occultations each day and global coverage every 6 hours. The mission cost is approximately $280M including launch, a fraction of the cost of a single JPSS satellite. To implement such a system for both climate and weather forecasting, we envision a public-private partnership as the technology is ready and critical demonstrations have been done.

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