The Atmospheric Boundary Layer: Climate, Weather and Applications

João Teixeira (Jet Propulsion Laboratory, California Institute of Technology, USA)
Chi Ao (Jet Propulsion Laboratory, California Institute of Technology, USA)
Anton Beljaars (ECMWF)
Christopher Bretherton (University of Washington, USA)
Axel von Engeln (EUMETSAT)
Matthew Lebsock (Jet Propulsion Laboratory, California Institute of Technology)
David Schimel (Jet Propulsion Laboratory, California Institute of Technology, USA)
Pier Siebesma (KNMI and Delft University of Technology, The Netherlands)
Graeme Stephens (Jet Propulsion Laboratory, California Institute of Technology)
Jordi Vila (Wageningen UR, The Netherlands)
Robert Wood (University of Washington, USA)

Description: The atmospheric boundary layer (ABL) plays a key role in weather and climate. Improved ABL parameterizations will lead to better weather/climate forecasts. Detailed observations of ABL temperature and water vapor structure are essential for progress. These observations are not yet available from space but are within our grasp in the next 10 years.

Key Challenges: The Atmospheric Boundary Layer
The atmospheric boundary layer (ABL) is the turbulent layer adjacent to the ocean, land and ice surface that mediates the interactions between the surface and the troposphere. The ABL depth varies depending on the nature and intensity of turbulence, but to first order is 1 to 2 km in ABL convective regimes.

The ABL is at the heart of key climate science challenges:

- Cloud-climate feedback (how clouds will respond and impact climate with increased greenhouse gas concentration) is essentially about the interactions between a highly turbulent flow with water phase transitions and radiation, often occurring in the ABL;
- The extreme weather and climate change problem is essentially about how deep moist convection, with its roots in the ABL, will respond to a warmer world;
- The exchanges of energy, water and carbon between the atmosphere, ocean, land, and ice are mediated by turbulent fluxes in the ABL;

The Intergovernmental Panel on Climate Change (IPCC) has reiterated that clouds are at the heart of the most significant source of uncertainty in current climate projections. ABL clouds play a key role in this cloud-climate feedback problem. Clouds are explicitly dependent on ABL temperature and water vapor structure, and more accurate knowledge of this structure is necessary to solve this problem.

In addition, the ABL plays a central role in all four guiding questions of the WCRP Grand Challenge on Clouds, Circulation, and Climate Sensitivity (Bony et al., 2015): (1)

What role does convection play in cloud feedbacks? (2) What controls the position, strength, and variability of the storm tracks? (3) What controls the position, strength and variability of the tropical rain bands? And (4) what role does convective aggregation play in climate?

Humans live in the ABL and the weather that we experience has a tremendous impact on our health, safety and economy. Weather forecasts are routinely produced by numerical weather prediction (NWP) centers around the world. The ABL plays a critical role in key weather events. The recent NASA Weather Focus Area community workshop report (Zeng et al., 2015) highlights the importance of the ABL for weather, and some key unsolved questions: How does moist convection interact with the ABL and the surface? What are the fundamental mechanisms controlling ABL clouds?

Acting as a buffer between the surface and the free troposphere, the ABL regulates atmospheric composition. Important processes (e.g. aerosol physics, entrainment) depend on ABL turbulence and convection, and its interplay with composition, radiation and clouds. In the context of applications, the ABL plays a key role in air quality as its turbulence and convection determine the transport of atmospheric constituents. Several other applications (e.g. health, renewable energy) require greater understanding of the ABL.

A long-term goal in the physics of weather and climate models is the development of accurate parameterizations that represent the processes associated with ABL turbulence, moist convection and clouds. However, current weather and climate models are still a long way away from realistically representing the ABL and many problems remain to be solved. Although some of these problems are theoretical, solving the key issues would benefit tremendously from better space observations of the fundamental properties of the ABL.

Timeliness

There are a few key reasons why this fundamental ABL challenge is timely to address in the next 10 years. First, it is absolutely essential to produce climate change projections that are much less uncertain than they are today. In this context, it is urgent to solve problems such as cloud-climate feedback. In order to be successful in addressing these goals a much better knowledge of the ABL is necessary. More detailed observations of the vertical structure of the ABL from space are essential.

From the NWP and data-assimilation perspective, it is now clear that, although far from perfect, current ABL parameterizations in NWP models are much improved compared to a few years ago. These better NWP models will allow for the assimilation of space-based ABL observations in a much more effective manner.

Solar and wind power are now major players in renewable energy production. In order to optimize energy production using wind and solar power, there is a crucial need for better ABL observations, which will lead to more accurate wind and solar power forecasts.

Space-Based Observations

The ABL is a global feature, including the world's oceans and remote land regions where in-situ observations are rare. For a global characterization of the ABL, space-based observations are essential. Since the ABL is often dominated by convective mixing, the ABL temperature and water vapor vertical structure determine and characterize many of the key physical processes (e.g. entrainment, clouds). To realistically characterize the ABL, from a global perspective, there is an urgent need for more accurate observations of the vertical profiles of ABL temperature and water vapor.

Surface evaporation, and sensible and latent heat fluxes mediate the water and energy exchange between the atmosphere and the surface. Improved estimates from space of surface heat, water and carbon fluxes are essential to improve weather and climate forecasts. Key components of surface fluxes calculations are the observations of temperature and water vapor close to the surface.

Existing space-based methods for remote sensing of temperature and water vapor profiles include passive infrared (IR) sounding, passive microwave (MW) sounding and radio occultation (RO) approaches. Each of these methods is extremely useful for assimilation in NWP and for climate analysis. Despite their successes, the current incarnations of these methods have limitations that preclude them from accurately profiling ABL temperature and water vapor. Current IR and MW sounding has fairly coarse horizontal resolution and broad weighting functions in the ABL. Additionally, clouds are frequent in the ABL, which influences IR spectra. RO is sensitive to ABL water vapor with high vertical resolution. However the utility of RO is challenged by an additional dependence on pressure and temperature, sampling issues and an even coarser horizontal resolution.

Given the recent history of the enormous impact of MW, IR and RO sounding in improving NWP forecasts, there is little doubt that more detailed information on the ABL temperature and water vapor structure, would have an additionally significant impact on weather forecasts. In fact, and in spite of the impact of current observations, few ABL observations are currently assimilated in NWP. This implies that much of the ABL structure produced by these models (which are also the source of re-analyses) derives directly from the parameterizations, with their implied model biases.

The recent NASA Weather Focus Area community workshop report (Zeng et al., 2015) recommends that continuous investment in temperature and water vapor profile measurements from space is needed, focusing on higher spatial and temporal resolution, and synergistic measurements involving multiple instruments, and different platforms (including small-sat and cubesats). The report states that in particular better measurements of ABL temperature and water vapor are needed.

However, currently planned national and international missions do not explicitly target the improvement of measurements of ABL vertical structure of temperature and water vapor and as such are not responsive to the needs discussed in this white paper.

Recent work using current technologies (IR, MW and RO) with higher spatial and temporal resolutions is encouraging, particularly when combined in an optimal way to probe more effectively into the ABL. Ultra high-resolution (order 100 m) IR sounders would be revolutionary in terms of temperature and water vapor horizontal structure, and would also produce more information on the vertical structure by finding many more clear regions, and using higher horizontal resolution to provide additional information on the vertical structure. New RO receiver technology currently under development would lead to improved accuracy and sensitivity within the ABL. Advances in technology, from the visible through the microwave spectrum, have recently enabled active sounding of water vapor in clear sky and within the cloudy ABL.

In summary, to solve key weather and climate ABL challenges, there is an urgent need for more accurate observations of ABL temperature and water vapor structure. This can be achieved in the next 10 years by investing in (i) optimal combinations of improved technologies that are currently already in use (e.g. higher resolutions and temporal sampling of IR, MW, RO approaches); and (ii) new technologies using active sensors.

Anticipated Science and Societal Benefits and Science Communities

As discussed above, the anticipated benefits of improved global observations of the ABL structure of temperature and water vapor are significant, from the weather, climate and applications perspective. For example, solving the cloud-climate feedback problem, which is deeply connected to the cloudy ABL, is of great urgency to improve climate projections.

The science communities associated with these essential weather and climate topics would be heavily involved in, and would greatly benefit from, this endeavor. The applications community (e.g. health, renewable energy) would be greatly served by the more detailed ABL measurements that are advocated in this white paper. These communities are part of research and development activities across a variety of agencies such as NASA, NOAA, NSF, DOE, EPA and DOD.

References

- Bony, S., and co-authors, 2015: Clouds, Circulation and Climate Sensitivity. *Nature Geoscience*, **8**, 261-268.
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